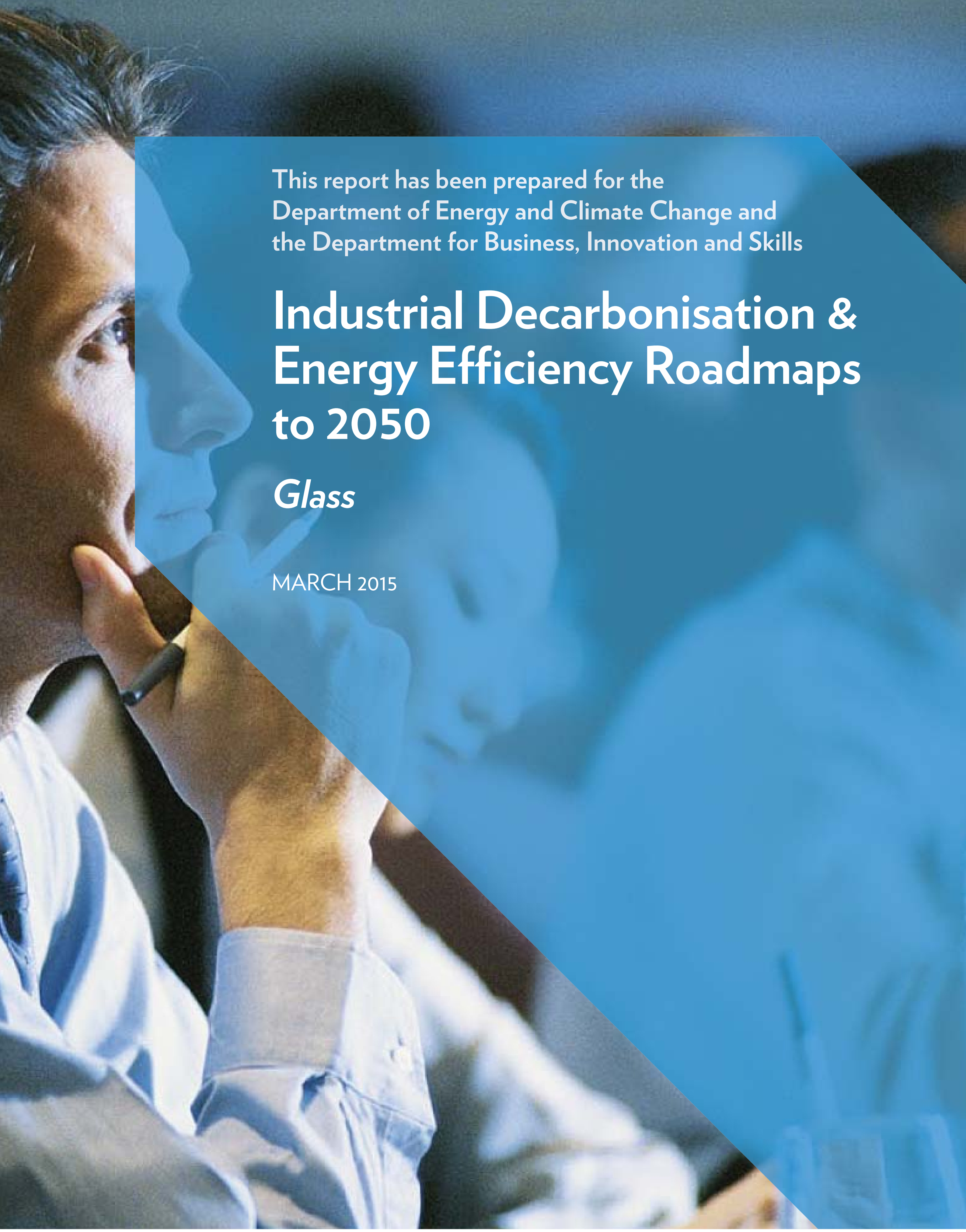

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Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

Glass

MARCH 2015

WSP | PARSONS BRINCKERHOFF

DNV·GL

CONTENTS

CONTENTS I

LIST OF FIGURES V

LIST OF TABLES VII

ACRONYMS VIII

1. EXECUTIVE SUMMARY 9

1.1 Introduction: What is the 'Decarbonisation and Energy Efficiency 9

1.2 Developing the Glass Sector Roadmap 9

1.3 Sector Findings 10

1.4 Enablers and Barriers for Decarbonisation in the Glass Sector 11

1.5 Analysis of Decarbonisation Potential in the Glass Sector 12

1.6 Conclusions and Key Technology Groups 13

2. INTRODUCTION, INCLUDING METHODOLOGY 17

2.1 Project Aims and Research Questions 17

2.1.1 Introduction 17

2.1.2 Aims of the Project 18

2.1.3 What is a Roadmap? 18

2.2 Overall Methodology 19

2.2.1 Findings 20

2.2.2 Pathways 24

2.2.3 Conclusions and Next Steps 27

3. FINDINGS 29

3.1 Key Points 29

3.2 Glass Manufacturing 30

3.2.1 Glass Manufacturing Processes 30

3.2.2 Technologies for Delivering Heat and Power 32

3.3 Current Emissions and Energy Use - Principal Question 1 32

3.3.1 Evolution of emission reductions 32

3.3.2 Emissions 33

3.3.3 Heat and Power Demand 34

3.3.4 Fuels Used 35

3.3.5 Lifespan of Equipment and Key Timings 35

3.4 Business Environment - Principal Question 2 36

3.4.1 Market Structure 36

3.4.2 Business Strategies 38

3.4.3 Decision-Making Processes 40

3.4.4 Financing Investments 42

3.4.5 Enablers and Barriers 43

3.5 Technologies to Reduce Carbon Emissions 53

3.5.1 Biomass Carbon Intensity 54

3.5.2 Costs of Options 55

4. PATHWAYS......56

4.1 Key Points 56

4.2 Pathways and Scenarios – Introduction and Guide 57

4.3 Baseline evolution - Principal Question 3 59

4.4 Emission-Reduction Potential and Pathway Analysis – Principal Question 4 and 5 60

4.4.1 Baseline - Business as Usual Pathway 61

4.4.2 20-40% CO_2 Reduction Pathway 64

4.4.3 40-60% CO_2 Reduction Pathway 65

4.4.4 60-80% CO_2 Reduction Pathway 68

4.4.5 Maximum Technical Pathway without CCS 70

4.4.6 Maximum Technical Pathway with CCS/U 72

4.5 Sensitivity Analysis 75

4.6 Pathway Costs 77

4.6.1 Introduction 77

4.6.2 Calculation of Pathway Costs 77

4.6.3 Limitations 78
4.6.4 Cost Analysis Results 79
4.7 Implications of Barriers and Enablers 80
4.7.1 Recycling (Cullet) 80
4.7.2 Improved Process Control 81
4.7.3 Waste Heat Recovery for Raw Materials Pre-Heating 81
4.7.4 Oxy-Fuel Combustion 82
4.7.5 Batch Pelletisation 82
4.7.6 Electric Melting 83
4.7.7 Batch Reformulation 83
4.7.8 Fuel Switching 84
4.7.9 Carbon Capture for Utilisation or Storage 84
4.7.10 Waste Heat Recovery – Non-Furnace 85
4.7.11 Conventional Improved Furnace Construction 85
4.7.12 Innovative Improved Furnace Construction 86
4.7.13 Others 86
5. CONCLUSIONS - PRINCIPAL QUESTION 6 88
5.1 Key Points 88
5.2 Strategic Conclusions 91
5.2.1 Strategic Leadership, and organisation 91
5.2.2 Business Case Barriers 91
5.2.3 Future Energy Costs, Energy Supply Security, Market Structure and Competition 92
5.2.4 Industrial Energy Policy Context 92
5.2.5 Life Cycle Accounting 93
5.2.6 Value Chain Collaboration 94
5.2.7 Research Development and Demonstration 95
5.2.8 Employees and Skills 96
5.3 Key Technology Groups 96
5.3.1 Electricity Grid Decarbonisation 96

5.3.2 Electrification of Heat (Electric Melting) 96
5.3.3 Fuel and Feedstock Availability (Including Biomass) 96
5.3.4 Energy Efficiency and Heat Recovery 97
5.3.5 Carbon Capture 97
5.3.6 Recycling 98
5.4 Closing Statement 99
6. REFERENCES 100
7. GLOSSARY 104
8. ACKNOWLEDGMENTS..107

LIST OF FIGURES

Figure 1 Overview of the different decarbonisation and energy efficiency pathways....12

Figure 2: Roadmap methodology....20

Figure 3: Evidence gathering process....22

Figure 4: Stages in the container glass manufacturing process (British Glass, 2014)....31

Figure 5: 2014 distribution of fuel type use in the UK glass industry (DECC, 2014)....35

Figure 6: The UK glass sector (British Glass, 2014)....37

Figure 7: Attitudes to innovation....40

Figure 8: Energy saving opportunities in glass manufacturing (Institute for Industrial Productivity, 2014)....54

Figure 9: Performance of pathways for the current trends scenario....56

Figure 10: Summary of analysis methodology....58

Figure 11: Reference trends for the different scenarios....61

Figure 12: Option deployment for the BAU pathway....62

Figure 13: Contribution of principal options to the absolute emissions reduction throughout study period, for the BAU pathway, current trends scenario....63

Figure 14: Breakdown of 2050 emissions reduction, for the BAU pathway, current trends scenario....63

Figure 15: BAU pathways for the different scenarios....64

Figure 16: Option deployment for the 40-60% CO_2 reduction pathway....65

Figure 17: Contribution of principal options to the absolute emissions reduction throughout study period, for the 40-60% CO_2 reduction pathway, current trends scenario....66

Figure 18: Breakdown of 2050 emissions reduction, for the 40-60% CO_2 reduction pathway, current trends scenario....67

Figure 19: 40-60% CO_2 reduction pathways for the different scenarios....67

Figure 20: Option deployment for the 60-80% reduction pathway....68

Figure 21: Contribution of principal options to the absolute reduction throughout the study period, for the 60-80% reduction pathway, current trends scenario....69

Figure 22: Breakdown of 2050 emissions reduction, for the 60-80% reduction pathway, current trends scenario....69

Figure 23: Option deployment for the Max Tech pathway without CCS/U....70

Figure 24: Contribution of principal options to the absolute throughout the study period, for the Max Tech 1 pathway, current trends scenario....71

Figure 25: Breakdown of 2050 emissions reduction, for the Max Tech pathway without CCS/U, current trends scenario....71

Figure 26: Max tech pathways without CCS/U for the different scenarios....72

Figure 27: Option deployment for the Max Tech pathway with CCS/U/CCU....73

Figure 28: Contribution of principal options to the absolute emissions reduction throughout the study period, for the Max Tech 2 pathway, current trends scenario....74

Figure 29: Breakdown of 2050 emissions reduction, for the Max Tech 2 pathway, current trends scenario...74

Figure 30: Max Tech pathway with CCS/U for the different scenarios....75

Figure 31: Pathways for current trends sensitivity analysis....76

LIST OF TABLES

Table 1: Energy-intensive industry total direct and indirect carbon emissions in 2012 (data sources include CCA, EU ETS and NAEI)....10

Table 2: Industrial sectors evaluated in this project....17

Table 3: Input and output for a decarbonisation and energy efficiency roadmap to 2050....19

Table 4: Emissions reduction activities....33

Table 5: UK glass companies in 2014 (British Glass, 2014)....34

Table 6: Specific energy and CO_2 consumption in the UK glass sector (DECC, 2014)....34

Table 7: Market share for container glass manufacturers (IBIS, 2013)....36

Table 8: Market share for flat glass manufacturers (IBIS, 2013)....36

Table 9: Sector sales growth data (Experian, 2014)....38

Table 10: Industry responses to energy efficiency and decarbonisation....42

Table 11: Top enablers....44

Table 12: Top barriers....49

Table 13: Pathways and scenario matrix....59

Table 14: Summary costs and impacts of decarbonisation for the pathways....80

ACRONYMS

APC	Adaptive Process Controller
ASD	Adjustable Speed Drive
BAT	Best Available Technology
BAU	Business as Usual
BCC	Biological Carbon Capture
BIS	Department of Business, Innovation and Skills
BTT	Breakthrough Technology and Techniques
CA	Compressed Air
CAPEX	Capital Expenditure
CCA	Climate Change Agreement
CCS/U	Carbon Capture and Storage/Utilisation
CCUS	Carbon Capture for Utilisation or Storage
CCU	Carbon Capture and Utilisation
CFC	ChloroFluoroCarbon
CGMS	Continuous Gob Monitoring System
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CPF	Carbon Price Floor
CPS	Carbon Price Support
CRC	Carbon Reduction Commitment
DECC	Department of Energy and Climate Change
EII	Energy Intensive Industries
ESP	Electro-Static Precipitator
EU ETS	European Union Emission Trading Scheme
FiT	Feed-in Tariffs
Forehearth	Set of narrow channels leading from the conditioning chamber to the forming machines
GVA	Gross Value Added
Homogenising	Creating uniform composition throughout the glass
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IGMC	Intelligent Glass Melting Concept
ITT	Invitation to Tender
LCA	Life Cycle Assessment
Lehr	A temperature-controlled kiln for annealing objects made of glass
ORC	Organic Rankine Cycle
RD&D	Research Development and Demonstration
REA	Rapid Evidence Assessment
Refining	Removal of impurities from molten glass
ROI	Return on Investment
SAT	State-of-the-Art Technologies
SCM	Submerged Combustion Melting
SIC	Standard Industrial Classification
SWOT	Strengths, Weaknesses, Opportunities and Threats
TCR	ThermoChemical Recuperator
TPV	ThermoPhotoVoltaic
TRL	Technology Readiness Level
VSD	Variable Speed Drive

1. EXECUTIVE SUMMARY

1.1 Introduction: What is the 'Decarbonisation and Energy Efficiency

This report is a 'decarbonisation and energy efficiency roadmap' for the glass sector, one of a series of eight reports that assess the potential for a low-carbon future across the most energy intensive industrial sectors in the UK. It investigates how the industry could decarbonise and increase energy efficiency whilst remaining competitive.

Changes in the international economy and the need to decarbonise mean that UK businesses face increasing challenges, as well as new opportunities. The UK Government is committed to moving to a low-carbon economy, including the most energy-intensive sectors. These sectors consume a considerable amount of energy, but also play an essential role in delivering the UK's transition to a low-carbon economy, as well as in contributing to economic growth and rebalancing the economy.

The roadmap project therefore aims to:

- Improve understanding of the emissions abatement potential of individual industrial sectors, the relative costs of alternative abatement options and the related business environment including investment decisions, barriers and issues of competitiveness.
- Establish a shared evidence base to inform future policy, and identify strategic conclusions and potential next steps to help deliver cost effective decarbonisation in the medium to long term (over the period from 2020 to 2050).

Each roadmap aims to present existing and new evidence, analysis and conclusions to inform subsequent measures with respect to issues such as industry leadership, industrial policy, decarbonisation and energy efficiency technologies, business investments, research, development and demonstration (RD&D) and skills.

This roadmap is the result of close collaboration between industry, academics and government (Department of Energy and Climate Change (DECC) and Department for Business, Innovation and Skills (BIS)), which has been facilitated and delivered by independent consultants Parsons Brinckerhoff and DNV GL; the authors of the reports.

1.2 Developing the Glass Sector Roadmap

The development of the glass sector roadmap consisted of three main phases:

1. Collection of evidence relating to technical options and enablers and barriers to invest in decarbonisation and energy efficiency technologies. Evidence was collected via a literature review, analysis of publicly available data, interviews and workshops. Discussion of evidence and early development of the decarbonisation potential took place during an initial workshop.
2. Development of decarbonisation and energy efficiency 'pathways' to 2050 to identify and investigate an illustrative technology mix for a range of emissions reduction levels. Draft results were discussed at a second workshop.
3. Interpretation and analysis of the technical and social and business evidence to draw conclusions and identify potential next steps. These example actions, which are informed by the evidence and analysis, aim to assist with overcoming barriers to delivery of technologies within the decarbonisation and energy efficiency pathways while maintaining competitiveness.

A sector team comprising representatives from the trade association (British Glass), the Government and Northumbria University has acted as a steering group as well as contributing evidence and reviewing draft project outputs. In addition, the outputs have been independently peer reviewed. It should be noted that the findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. Where possible we have tried to include alternative findings or viewpoints, but this has not always been possible; this needs to be taken into account when reading this report.

1.3 Sector Findings

The glass sector produces container glass (bottles and jars), flat glass (windows for construction automotive), fibre glass (e.g. for wind turbines), and domestic/specialty glass products. The sector is characterised by the use of high-temperature melting furnaces and other heat-intensive processing equipment (like forehearths and lehrs), accounting for ca. 85% of all the fuels used (British Glass, 2014). Most furnaces are fired with natural gas (with fuel oil as standby fuel). Electricity is also used in the process. The combustion of fossil fuel, raw material degradation and indirect emissions from electricity consumption makes up the glass sector carbon footprint shown in Table 1.

SECTOR	TOTAL ANNUAL CARBON EMISSIONS 2012 (MILLION TONNES CO_2)
Iron and Steel[1]	22.8
Chemicals	18.4
Oil Refining	16.3
Food and Drink	9.5
Cement[2]	7.5
Pulp and Paper	3.3
Glass	**2.2**
Ceramic	1.3

Table 1: Energy-intensive industry total direct and indirect carbon emissions in 2012 (data sources include CCA data, EU ETS and NAEI)

Glass manufacturing processes depend highly on the final product, but all manufacturing processes have a common origin: glass first needs to be melted. Glass melting requires raw materials (different types of sand and minerals and/or recycled glass), mixed together and charged in a furnace where they are melted at ca. 1,500°C. The molten glass is then taken out of the furnace to be shaped and cooled down, possibly further processed to have specific properties. The UK glass sector produced over three million tonnes of different

[1] For the iron and steel sector, the reference year used is 2013. This was chosen due to the large production increase from the re-commissioning of SSI Teesside steelworks in 2012.
[2] For the cement sector, the 2012 actual production levels where adversely affected by the recession. Therefore we have assumed production of 10 million tonnes (rather than the actual production in 2012) and normalised emissions to this production level.

products in 2012: 65% comprised container glass, 30% flat glass and the remaining 5% fibre and domestic/speciality glass (British Glass, 2014).

Glass is an energy-intensive sector; energy is one of the largest operational costs in glass making. In 2012 it was estimated to emit 1.7 million tonnes/year of carbon dioxide, with a further 0.5 million tonnes/year emitted in electricity production for use within the sector (British Glass 2014).

The UK glass industry is a mature market, with high capital intensity requirements. It is dependent on trends in downstream construction, automotive, wind energy, beverage, and fruit and vegetable processing sectors as these are the primary customers of glass. UK glass revenues were £853.4 million for container glass and £316 million for flat glass in 2013 (British Glass, 2014).

During the recession, due to the depression of the construction industry, demand for flat glass fell sharply. The economic recovery is seeing an increase in the demand for flat glass with 3.7% annual growth estimated between 2014 and 2019. Flat glass manufacturers expect that there may be strong growth in the next few years and then a stabilisation of demand. Key drivers for growth include demand from building and construction and automotive sectors. The growth prospects for flat glass depend on the sector's ability to compete with import competition, and expanding into downstream shaped and processed flat glass products.

Key drivers for growth include demand from food and beverage packagers and retailers. The long-term growth prospects for the container glass industry hinges on the continued capability of bottle and jar manufacturers to compete against alternative packaging materials.

The growth of the wind energy market, electronics, and bathroom industries will directly impact on the growth prospects of fibre glass in the UK.

1.4 Enablers and Barriers for Decarbonisation in the Glass Sector

In this report, we look at 'enablers', 'barriers' and 'technical options' for decarbonisation of the glass sector. There is some overlap between barriers and enablers, as they sometimes offer two perspectives on the same issue. Based on our research, the main enablers for decarbonisation for the glass sector include:

- Customer demand for more sustainable products
- Alternative financing and access to capital
- Proven and financially viable technologies
- Increasing lifespan of equipment
- Regulations encouraging energy efficiency in downstream sectors
- High and increasing energy prices
- Strong recycling infrastructure
- Commitment by top management to an environmental policy or climate change strategy
- Stable energy efficiency and carbon regulatory framework
- Legislative compliance
- Replacement of obsolete equipment
- High carbon price

The main barriers to decarbonisation have been identified as:

- Lack of demand for low carbon products.
- Long payback periods and high costs
- High and fluctuating energy prices
- Uneven playing field with overseas competition

- Insufficient quantities of high-quality cullet
- Risk of production disruption, hassle and inconvenience
- Retrofit capability
- Difficulty to find external financing
- Long plant life or investment cycle
- Lack of capital
- Chemical and process efficiency limitations
- Low demand risk

1.5 Analysis of Decarbonisation Potential in the Glass Sector

A 'pathway' represents a particular selection and deployment of options from 2012 to 2050 chosen to achieve reductions falling into a specific carbon reduction band relative to a reference trend in which no options are deployed. Two further pathways with specific definitions were also created, assessing (i) what would happen if no particular additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech). These pathways include deployment of options comprising (i) incremental improvements to existing technology, (ii) upgrades to utilise BAT, and (iii) the application of significant process changes using 'disruptive' technologies that have the potential to become commercially viable in the medium term.

The pathways created in the current trends scenario, the central of three scenarios used in this study, are shown below in Figure 1[3].

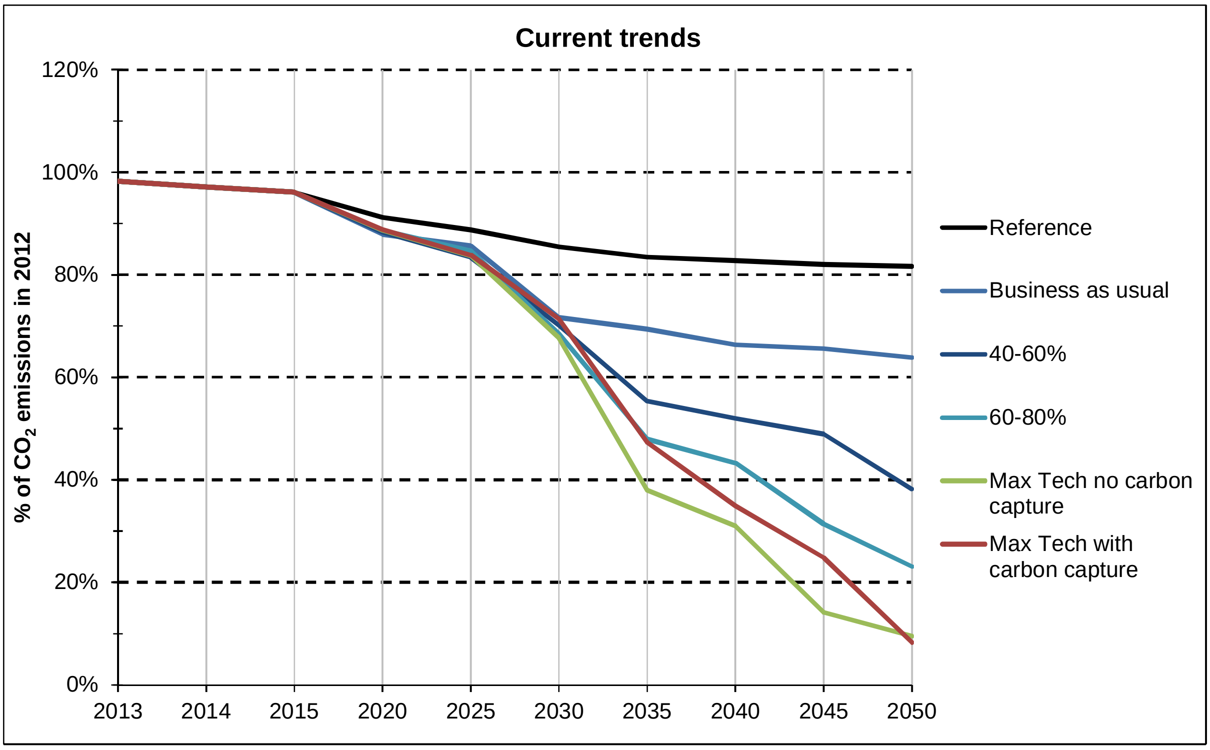

Figure 1 Overview of the different decarbonisation and energy efficiency pathways

[3] Two versions of Max Tech are shown illustrating alternative pathways

Analysis of the costs of the pathways used order of magnitude estimates to add up the capital cost of each pathway. As an indication, the net present capital cost for the pathways, discounted at 3.5%, falls within an estimated range of £30 million[4] to £200 million[5]. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the research and development stage. Also, costs of operation, energy use, research, development, demonstration, civil works, modifications to plant and costs to other stakeholders are significant for some options, but not included here. The costs presented are for the study period and are adjusted to exclude residual value after 2050, thus a proportion of the costs of high capex items deployed close to 2050 is excluded. Great care must be taken in how these costs are interpreted. While implementation of some of the options within the pathways may reduce energy costs due to increased efficiency, the scale of the investments associated with the pathways must be considered by stakeholders when planning the next steps in the sector

1.6 Conclusions and Key Technology Groups

The following conclusions have been drawn from the evidence and analysis:

Strategy, Leadership and Organisation

It is critical that the glass sector, the government and other stakeholders recognise the importance of strategy and leadership in the context of decarbonisation, energy efficiency and general competitiveness for the sector.

Business Case Barriers

One of the most important barriers to decarbonisation and increased energy efficiency is lack of funding for such projects as the return of investment is not attractive enough or there is a lack of access to capital.

Future Energy Costs, Energy Supply Security, Market Structure and Competition

It is clearly critical to ensure that future decarbonisation and energy efficiency actions maintain the position with respect to overall cost-competitiveness of the UK sector compared to competing businesses operating in other regions of Europe, Asia and the US. This strategic conclusion links to a number of external factors that influence the business environment in which the sector operates. These include energy security and energy cost comparison to other regions (both reality and perception), as these factors are important when investment decisions are made.

Industrial Energy Policy Context

Many in the sector have emphasised that a long-term energy and climate change policy is key to investor confidence. Also, a number of stakeholders believe that there is a need for incentive schemes to become long-term commitments, as changes in policy can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy related costs.

Life-Cycle Accounting

The interaction between sectors is significant, with the carbon emissions of the glass sector being necessary to make products which reduce carbon emissions in other sectors. For example, energy efficient flat glass for windows is a more complex product than normal glass, and requires more energy to manufacture. However,

[4] For the BAU pathway in the current trends scenario
[5] For the Max Tech pathway in the current trends scenario

when installed as an energy efficient window in a building, this will save more energy in use than the total energy required to manufacture the glass.

Value Chain Collaboration

Recycled glass: There is an opportunity for the sector to reduce carbon emissions by increasing the use of recycled glass (cullet). Closed loop recycling (recycling glass back to glass) is preferred as it results in greater energy savings and CO_2 reduction than using recycled glass as aggregate.

Creating markets for low carbon glass products: The majority of customers and consumers would not preferentially choose a low carbon product over a similar product manufactured to lower environmental standards. If consumers were willing to pay extra for low-carbon products, this could help fund energy efficiency and CO_2 reduction. Creating markets for low carbon glass products could improve the business case for investing in additional environmental projects.

Research, Development and Demonstration

Many of the options identified in the pathway analysis require development of new technologies and processes. The interviews and workshops have identified that progressing the necessary RD&D into decarbonisation technologies is an important enabler. There is also a need to support funding of these activities. Creating an enabling environment is primarily related to actions that can be taken by industry, government, and other stakeholders to help progress decarbonisation technologies and improve market demand for 'greener' glass products.

People and Skills

There is a limited number of staff with specialised skills in energy and furnace engineering in the sector. The priorities of those staff tend to be on ensuring compliance with regulations which diverts attention and effort away from identification and implementation of energy efficiency opportunities.

The key technology groups that, in this investigation, make the largest contributions to sector decarbonisation or energy efficiency are as follows:

Electricity and gas grid decarbonisation

Low-carbon energy supply is critical to the glass sector and actions are required to maintain a competitive position for the UK. Certain options, such as electric melting, will not reduce carbon emissions without grid decarbonisation. Actions will be required to ensure that this takes place while maintaining cost-competitiveness. The Government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

Electrification of Heat

Electric melting is a key decarbonisation technology, and was assumed in this study to be available for commercial implementation post-2030. The main barriers to implementation include late state research and development needs including scale-up, the current carbon intensity of the UK electricity supply meaning that electric melting has a higher carbon impact than conventional natural-gas fired furnaces and the current and projected high cost of electricity compared to natural gas.

Fuel and feedstock availability (including biomass)

Understanding how much low-carbon fuel and feedstock will be available to the sector is an important first step in addressing a key barrier to the pathways that include the use of (on-site generated) biogas or bio-methane as a fuel substitution option for glass melting. At present, as identified in the sector workshops, there is a lack of clarity on the long-term availability, cost and technical viability of resources such as biomass and the degree to which it can be considered low carbon. It will also be necessary to understand, both within the glass sector, other industries and across the wider economy, where these fuels and feedstocks can be used to achieve the greatest decarbonisation impact (links to *Life-cycle carbon accounting* above). There is significant added value to use biomass for heat and power (via CHP technology) compared to power generation only, and this is recognised in government electricity market support policy.

Energy Efficiency and Heat Recovery Technology

Energy efficiency and heat recovery technologies have been identified in the roadmap as a significant potential contributor to decarbonisation. This option covers a group of technologies which are generally well-established and so there is a relatively low technical risk with their implementation. By reducing energy use, these options can provide operational cost savings. Waste heat recovery is already practiced by the glass sector, but further opportunities exist and, in addition, waste heat can be utilised for electricity production. The main barriers are high capital costs of equipment, long paybacks, practical and technical issues.

Carbon Capture

Carbon capture has a large emissions reduction potential, however; it also has many barriers that need to be overcome before it can be viable. Glass companies expressed a preference to avoid carbon capture in favour of other decarbonisation technologies because of perceived cost and disruption of carbon capture equipment and its mutual exclusivity with electric furnaces. However, if other options cannot be implemented, then it may be necessary for the glass sector to implement carbon capture, and it is therefore important that the technology option is not ignored, and the potential implementation of carbon capture given consideration.

The scale of CO_2 emissions in the glass sector is such that the implementation of carbon capture at a glass manufacturing site would be insufficient to justify the implementation of a full CCS chain. This can be addressed if the glass facility is located within a larger industrial cluster to access a shared CO_2 transportation and storage network or by implementing utilisation of captured CO_2 (CCU) rather than storage. The smaller volumes of CO_2 captured when compared against other emitters are more likely to align with the CO_2 feedstock requirements of potential future CO_2 utilisation industries.

Recycling

Results from literature, interviews and workshops gave a consistent message that there is an opportunity for the sector to reduce carbon emissions by increasing the use of recycled glass (cullet). Closed loop recycling (recycling glass back to glass) is preferred as it results in greater energy savings and CO_2 reduction than using recycled glass as aggregate.

To increase the amount of glass available to and recycled within the UK glass sector, various barriers need to be overcome. Existing recycling systems could be improved, new glass streams (e.g. building glass) could be recycled, and technologies could be improved to aid processing. The complex situation and economics needs to be studied further to identify constructive ways to move forward.

Over 1 million tonnes of glass was recycled back to glass in the UK in 2012 (British Glass, 2014). However, the limiting factor is the availability of competitively priced, uncontaminated recycled glass. If more recycled glass was available in the UK, more could be used in glass manufacturing.

Next Steps:

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The report has been compiled with the aim that is has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy.

2. INTRODUCTION, INCLUDING METHODOLOGY

2.1 Project Aims and Research Questions

2.1.1 Introduction

Changes in the international economy, coupled with the need to decarbonise, mean that UK businesses face increased competition as well as new opportunities. The government wants to enable UK businesses to compete and grow while moving to a low-carbon economy. The UK requires a low-carbon economy but currently includes industries that consume significant amounts of energy. However, these industries manufacture essential products from wind turbines to energy efficient windows. These energy-intensive industries have an essential role to play in delivering the UK's transition to a low-carbon economy, as well contributing to economic growth and rebalancing the economy.

Overall, industry is responsible for nearly a quarter of the UK's total emissions (DECC, 2011)[6]. By 2050, the government expects industry to have delivered a proportionate share of emissions cuts, achieving reductions of up to 70% from 2009 levels (DECC, 2011). Nonetheless, the government recognises the risk of 'carbon leakage' and 'investment leakage' arising from the need to decarbonise and is committed to ensuring that energy-intensive industries are able to remain competitive during the transition to a low-carbon economy.

The Department of Energy and Climate Change (DECC) and the Department of Business, Innovation and Skills (BIS) have set up a joint project focusing on the eight industrial sectors which use the greatest amount of energy[7]. The project aims to improve the understanding of technical options available to sectors to reduce carbon emissions and increase energy efficiency while remaining competitive. This includes include investigating the costs involved, the related business environment, and how investment decisions are made in sector firms. This will provide the industry and government with a better understanding of the technical and economic abatement potential, set in the relevant business context, with the aim to agree measures that both the government and these industries can take to reduce emissions while maintaining sector competitiveness.

The project scope covers both direct emissions from sites within the sector and indirect emissions from the use of electricity at the sites but generated off site.

The industrial sectors evaluated in this project are listed in Table 2.

Cement	**Glass**
Ceramics	Iron and Steel
Chemicals	Oil Refining
Food and Drink	Pulp and Paper

Table 2: Industrial sectors evaluated in this project

[6] It has also been estimated that 70% of industrial energy use is for heat generation (Source: Energy Consumption in the UK 2014: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk)
[7] The 'non-metallic minerals' sector has been divided into three sectors: glass, ceramics and cement.

2.1.2 Aims of the Project

The DECC 2011 Carbon Plan outlined the UK's plans to reduce greenhouse gas emissions and make the transition to a low-carbon economy while maintaining energy security and minimising negative economic impacts.. This project aims to improve evidence on decarbonisation and energy efficiency for eight energy-intensive industry sectors, with glass being the subject of this report.

The project consortium Parsons Brinckerhoff and DNV GL was appointed by DECC and BIS in 2013 to work with stakeholders, including the UK manufacturers' organisations (i.e. trade associations), to establish a shared evidence base to support decarbonisation. The roadmap process consisted of three main phases:

i. Information and evidence gathering on existing technical options and potential breakthrough technologies, together with research to identify the social and business barriers and enablers to decarbonisation
ii. Development of sector decarbonisation and energy efficiency pathways
iii. Conclusions and identification of potential next steps

A series of questions were posed by DECC and BIS as part of the project. These 'principal questions' guided the research undertaken and the conclusions of this report. The questions and the report section in which they are addressed are stated below:

4. What are the current emissions from each sector and how is energy used? - section 3.3
5. For each sector, what is the business environment, what are the business strategies of companies, and how does it impact on decisions to invest in decarbonisation? - section 3.4
6. How might the baseline level of energy and emissions in the sectors change over the period to 2050? - section 4.3
7. What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050? - section 4.4
8. What emissions pathways might each sector follow over the period to 2050 under different scenarios? - section 4.4
9. What next steps into the future might be required by industry, the government and others to overcome the barriers in order to achieve the pathways in each sector? - section 5

2.1.3 What is a Roadmap?

A 'roadmap', in the context of this research, is a mechanism to visualise future paths, the relationship between them and the required actions to achieve a certain goal. A technology roadmap is a plan that matches short-term and long-term goals with specific technology solutions to help meet those goals. Roadmaps for achieving policy objectives go beyond technology solutions into broader consideration of strategic planning, market demands, supplier capabilities, and regulatory and competitive information.

The roadmaps developed by this project investigate decarbonisation in various UK industries, including how much carbon abatement potential currently exists, what technologies will need to be implemented in order to extend that potential, and how businesses will be affected. The roadmap aims to present existing and new evidence, analysis and conclusions as a 'consensual blueprint' to inform subsequent action with respect to issues such as future energy and manufacturing industrial strategy and policy, decarbonisation and energy efficiency business investments, research and development, and skills. The roadmaps consist of three components: evidence, pathways analysis and conclusions, as illustrated in Table 3. Each component is necessary to address the principal questions, and is briefly defined below.

INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050			
SOURCES OF EVIDENCE	**INTERMEDIATE OUTPUTS**	**PATHWAYS**	**STRATEGIC CONCLUSIONS AND EXAMPLE ACTIONS**
Literature	Validated emission data	Analysis of evidence to construct decarbonisation and energy efficiency pathways	Analysis of evidence and pathways to develop strategic conclusions and possible next steps to: • Overcome barriers and strengthen enablers • Implement pathways
Publicly available emissions data	Decarbonisation options and associated data		
Interviews, survey, meetings and workshops with stakeholders	Energy efficiency options and associated data		
Government policy and analytical teams, trade associations, academics as part of engagement with the sector team	Barriers and enablers to decarbonisation and energy efficiency options and investment		

Table 3: Input and output for a decarbonisation and energy efficiency roadmap to 2050

The views of contributing organisations

These reports were commissioned by DECC and BIS, and jointly authored by Parsons Brinckerhoff and DNV GL. The project was progressed using a collaborative process and while important contributions were provided by the sector, it should not be assumed that participating organisations (i.e. government, trade associations and their members and academic institutions) endorse all of the report's data, analysis and conclusions.

The findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. We have tried to include alternative findings or viewpoints, but this has not always been possible within the constraints of the project. This needs to be taken into account when reading this report.

2.2 Overall Methodology

The overall methodology is illustrated in Figure 2 and shows the different stages of the project. As can be seen, the stakeholders are engaged throughout the process that follows the main phases of the project: evidence gathering, modelling/pathway development and finally drawing out the conclusions and potential next steps. A detailed description of the methodology can be found in appendix A.

Figure 2: Roadmap methodology

Evidence was gathered for covering technical, and social and business aspects from literature reviews, interviews, survey and workshops with relevant stakeholders. These different sources of information allowed evidence triangulation to improve the overall research. The data was then used to develop a consolidated list of barriers and enablers for decarbonisation, and a register of technical options for the industry. This was subsequently used to develop a set of decarbonisation and energy efficiency pathways to evaluate the decarbonisation potential of the UK glass sector and the main technical options required within each pathway.

Key to the overall roadmap methodology was engagement with all stakeholders, including with business and trade association representatives, academics and civil servants, to contribute to the evidence, validate its quality and interpret the analysis. We have worked closely with British Glass, DECC and BIS to identify and involve the most appropriate people from the glass sector, relevant academics and other stakeholders, such as representatives from the financial sector.

2.2.1 Findings

Evidence Gathering

The data focused on technical, and social and business information, aiming to acquire evidence on:

- Decarbonisation options (i.e. technologies)

- Barriers and enablers to decarbonisation and energy efficiency
- Background to the sector
- Current state of the sector and possible future changes within the sector
- Business environment and markets
- Potential next steps

Such evidence was required to either answer the principal questions directly and/or to inform the development of pathways for 2050. Four methods of research were used in order to gather as much evidence as possible (and to triangulate the information) within a short timescale. These methods were:

- **Literature review:** A short, focussed review of over 85 documents all published after 2000 (with minor exceptions) was completed. The documents were either related to energy efficiency and decarbonisation of the sector or to energy-intensive industries in general. This was not a thorough literature review or rapid evidence assessment (REA) but a desktop research exercise deemed sufficient by the project team[8] in its breadth and depth to capture the evidence required for the purpose of this project. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. This included the sector structure, recent history and context including consumption, demand patterns and emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation. Further details are provided in appendix A.
- **Interviews:** In liaison with British Glass, DECC and BIS, eight semi-structured interviews were initially conducted representing technical operations via environment and energy managers from different glass companies and the trade association. The purpose of the interviews was to obtain further details on the different subsectors within the glass sector and gain a deeper understanding of the principal questions, including details of decision-making processes and how companies make investment decisions, how advanced technologies are financed, what a company's strategic priorities are and where climate change sits within this. The interviewees were interviewed using an 'interview protocol' template, developed in liaison with DECC and BIS. This template was used to ensure consistency across interviews, fill gaps in the literature review, identify key success stories and extract key barriers to investment in low-carbon technologies. The interview protocol can be found in appendix A. Interviewees were selected to maximise coverage across sub-sectors and emissions and also take into account company headquarters location, production processes and company size.
- **Survey:** As part of the evidence gathering exercise and to help build a list of the enablers and barriers, a short bespoke survey was conducted with the main UK glass manufacturing industries. The questions were drawn up in consultation with DECC and BIS and the sample of respondents were selected based on coverage of a high proportion of sector emissions (nb the survey was not a census). The key questions focused on the respondents view on the level of impact of the top enablers and barriers on the implementation of energy efficiency and decarbonisation options as identified from the interviews and literature review. The number of respondents was 17 out of the 50 survey requests that were sent to workshop participants. The low response rate was due to the limited time between when the survey was issued and when the workshop was held. The survey included those that were interviewed.
- **Workshops:** Two workshops were held, attendees for which were identified in consultation with British Glass, DECC and BIS. The first workshop focused on reviewing potential technological decarbonisation and energy efficiency options (that had been provisionally generated from the literature review) and discussing adoption rate, applicability, improvement potential, ease of

[8] DECC, BIS and the consultants of PB and DNV GL.

implementation, capex, return on investment (ROI), savings potential and timeline for the different options. This was done through two breakout sessions: one focused on collecting more data and the other one on timelines under different scenarios. The second activity involved group discussions on enablers and barriers to energy efficiency and decarbonisation investment, and how to overcome them. The second workshop focused on reviewing the draft pathways and identifying potential actions for delivering them. The workshop participants included the relevant trade associations, large companies with the aim of achieving representation of key companies or subsectors and academics with expert knowledge of the sector, PB and DNV GL consultants, DECC and BIS project managers and senior civil servants. The average size of a workshop was 40 people.

By using a range of information sources, the evidence could be triangulated to improve the overall research. Themes that were identified during the literature review were subsequently used as a focus or a starting point during the interviews and workshops. The data from the literature was corroborated by comparing it with evidence from the interviews and workshops. Likewise, information gaps identified during the interviews and workshops were, where possible, populated using literature data. In addition, British Glass collected data from its members that further helped to fill gaps and triangulate multiple data sources. It should be noted that the evidence-gathering exercise was subject to several limitations based upon the scale of activities that could be conducted within the time and resources available. Interview and survey samples were gathered through purposive and snowball sampling techniques in collaboration with trade associations, DECC and BIS experts. But due to time, sampling and resource constraints the samples may be limited in terms of their numbers and/or diversity. Where possible we have attempted to triangulate the findings to counter any bias in the sample, but in some areas this has not been possible. Some caution should therefore be used in interpreting the findings. The literature review, while not intended to be exhaustive, aimed to capture key documentation that applied to the UK. The criteria for identifying and selecting literature is detailed in Appendix A.

The different sources of evidence together with the associated outputs are shown in Figure 3.

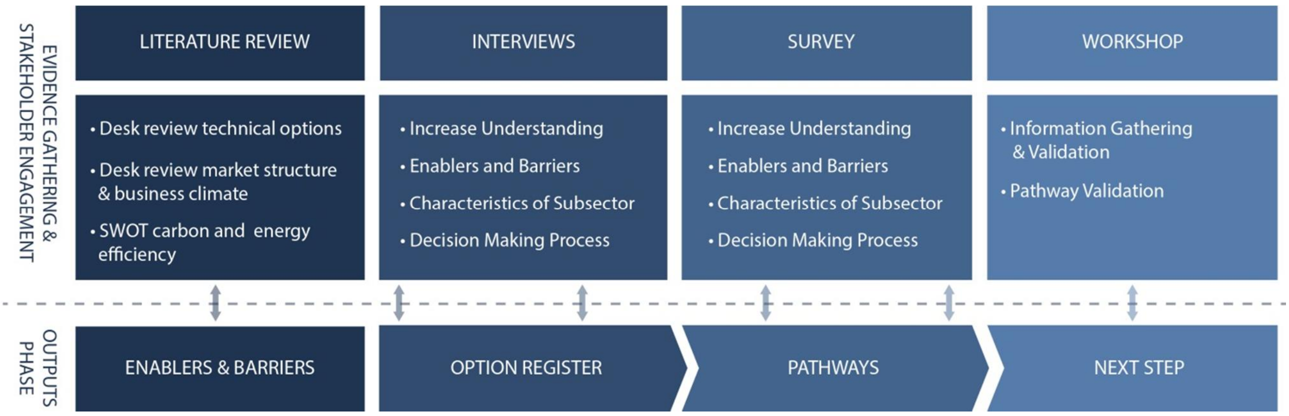

Figure 3: Evidence gathering process

The different sources of evidence were used to develop a consolidated list of barriers to and enablers for decarbonisation and energy efficiency, and a register of technical options for the glass sector. Evidence on adoption rate, applicability, improvement potential, ease of implementation, capex, ROI and saving potential of all options (where available) was collected, together with information on strengths, weaknesses, opportunities and threats (SWOT). A SWOT analysis is a different lens to examine the enablers and barriers and reinforce conclusions and linkages between evidence sources. It identifies how internal strengths mitigate external threats and can be used to create new opportunities, and how new opportunities can help overcome weaknesses. By clustering the various possibilities, we identified key stories from the SWOT analysis which enabled us to describe the business and market story in which companies operate. Further information on the SWOT analysis is provided in appendix B. The SWOT analysis was used to further understand and validate the initial findings from the literature review and provided the basis for workshop and interview discussions and developing the survey, and further helped to qualify the interview and workshop outcomes. Enablers and barriers were prioritised as a result of the outcomes and analysis of the evidence-gathering process and workshop scores.

This information was used to inform the development of a set of pathways to illustrate the decarbonisation potential of the glass sector in the UK. The summary and outcomes of this analysis are discussed in Section 4.

The evidence-gathering process was supported by high levels of engagement with a wide range of stakeholders including industry members, trade association representatives, academics and staff of DECC and BIS.

The evidence-gathering exercise (see appendix A for details) was subject to inherent limitations based upon the scale of activities and sample sizes that could be conducted within the time and resources available. The glass companies interviewed, represented over 75% of carbon emissions produced in the UK, and included UK decision-makers and technical specialists in the glass sector. These interviews were conducted to provide greater depth and insight to the issues faced by companies.

The identification of relevant information was approached from a 'global' and UK viewpoint. The global outlook examined dominating technologies and process types, global production, CO_2 emissions (in the EU28), and the global outlook to 2050, including the implications for pulp and paper producers and consumers. The UK outlook examined the sector structure, recent history and context including consumption, demand patterns, emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation.

Options examined were classified into eight categories that represent the principal areas of the glass making process and key cross-cutting areas of potential performance improvement, in order to group similar technology options (see appendix C): raw materials, furnace, improved process control, waste heat recovery, fuel switching, carbon capture, general utilities, recycled glass, and product design.

Evidence Analysis

The first stage in the analysis was to assess the strength of the evidence for the identification of the enablers and barriers. This was based on the source and strength of the evidence, and whether the findings were validated by more than one information source. The evidence was also analysed and interpreted using a variety of analytical techniques. Elements of the Porter's five forces analysis, SWOT analysis and system analysis were used to conduct the analysis of the business environment, and the barriers and enablers (section 3.4); while concepts from storytelling and root cause analysis were used during the interviews with stakeholders. These different techniques are discussed in appendix B.

The options register of the technology options for decarbonisation was developed based on the literature review, interviews, the evidence gathering workshop, and additional information provided by British Glass and its members. The strengths, weaknesses, enablers and barriers of each option were taken into account to refine the options register, which was then used to build up the different pathways in the pathway model.

A second stage in the analysis was the classification of technological options and an assessment of their readiness.

Limitations of these Findings

The scope of the study did not cover a full assessment of the overall innovation chain or of present landscape of policies and actors. Direct and indirect impacting policies, gaps in the current policy portfolio, and how future actions would fit into that portfolio (e.g. whether they would supplement or supplant existing policies) are not assessed in the report in any detail.

2.2.2 Pathways

The pathways analysis is an illustration of how the glass industry could potentially decarbonise from the base year 2012 to 2050. Together the set of pathways developed in the study help give a view of the range of technology mixes that the sector could deploy over coming decades. Each pathway consists of different technology options that are implemented over time at different levels. Each technology option included a number of key input parameters including carbon dioxide reduction, cost, fuel use change, applicability, current adoption (in the base year), and deployment (both rate and extent). A 'pathway' represents a particular selection and deployment of options from 2014[9] to 2050 chosen to achieve reductions falling into a specific decarbonisation band.

In this project, up to five pathways were developed, three of which were created to explore possible ways to deliver carbon dioxide emissions to different decarbonisation bands by 2050, as shown below:

- 20-40% CO_2 reduction pathway relative to the base year
- 40-60% CO_2 reduction pathway relative to the base year
- 60-80% CO_2 reduction pathway relative to the base year

Two further pathways - with specific definitions - were also created, assessing (i) what would happen if no additional interventions are taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech)[10].

The BAU pathway consisted of the continued roll-out of technologies that are presently being deployed across the sector as each plant or site reaches the appropriate point to implement the technology. For the glass industry, two different Max Tech pathways were developed to illustrate the impact of whether carbon capture is considered to be applicable within the glass sector, or whether decarbonisation is achieved using options excluding carbon capture.

Pathways were developed in an iterative manual process and not through a mathematical optimisation process. This was done to facilitate the exploration of uncertain relationships that would be difficult to express analytically. This process started with data collected in the evidence gathering phase regarding the different decarbonisation options, current production levels and the current use of energy or CO_2 emissions of the sector. This data was then enriched through discussion with the sector team and in the first workshop. Logic reasoning (largely driven by option interaction), sector knowledge and technical expertise were applied when selecting technical options for the different pathways. These pathways were discussed by the sector team, modelled, and finally tested by the stakeholders participating in the second workshop. This feedback was then taken into account and final pathways were developed. All quantitative data and references are detailed in the options register and relevant worksheets of the model. The pathway model is available through DECC and BIS and the methodology is summarised in appendix A

[9] Model anticipates deployment from 2014 (assuming 2012 and 2013 are too early).
[10] Definitions are provided in the glossary.

Scenario Testing

The different pathways developed have been tested under different scenarios (i.e. there are three different scenarios for each pathway). A scenario is a specific set of conditions that could directly or indirectly affect the ability of the sector to decarbonise. Examples of these are: future decarbonisation of the grid, future growth of the sector, future energy costs, and future cost of carbon. Since we do not know what the future will look like, using scenarios is a way to test the robustness of the different pathways.

For each pathway, the following three scenarios were tested (a detailed description of these scenarios is provided in appendix A):

- **Current trends**: This would represent a future world very similar to our world today with low continuous growth of the industry in the UK.
- **Challenging world**: This would represent a future world with a more challenging economic climate and where decarbonisation is not a priority and the industry is declining in the UK.
- **Collaborative growth**: This would represent a future world with a positive economic climate and where there is collaboration across the globe to decarbonise and where the industry has a higher growth rate in the UK.

In order to produce pathways for the same decarbonisation bands under the different scenarios, the deployment rate of the options varied according to the principals set out in the scenarios. For example, in order to achieve a specific decarbonisation band in 2050 in the collaborative growth scenario, options were typically deployed at a faster rate and to a higher degree as compared to the current trends scenario (provided this was considered to be consistent with the conditions set out in the scenarios).

Key Assumptions and Limitations

The pathway model was developed and used to estimate the impact on emissions and costs of alternative technology mixes and macro-economic scenarios. Modelled estimates of decarbonisation over the period (2014 to 2050) are presented as percentage reductions in emissions meaning the percentage difference between emissions in 2050 and emissions in the base year (2012). CO_2 emissions reductions and costs are reported compared to a future in which there was no further take up of decarbonisation options (referred to as the reference trend).

The model inputs and option deployments are based on literature review, interviews and stakeholder input at workshops and sector meetings. Parsons Brinckerhoff and DNV GL sector leads used these sources to inform judgements for these key parameters. Key input values (e.g. decarbonisation factors for options) are adapted from literature or directly from stakeholder views. If data values were still missing then values were estimated based on consultant team judgements. Decarbonisation inputs and pathways were reviewed and challenged at workshops. The uncertainties in this process are large given this level of judgement, however, uncertainties are not quantified. A range of sensitivity analysis was carried out including the development of alternative versions of the Max Tech pathway and also testing of different availabilities of biomass.

Deployment of options at five-year intervals is generally restricted to 25% steps unless otherwise indicated. For example, an option cannot be incrementally deployed by 25% over ten years, but has to deploy over five years and flat-line over the other five years.

In this report, when we report carbon dioxide – this represents CO_2 equivalent. However, other GHGs were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site. Also, technical options assessed in this work result primarily in CO_2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO_2, are very low.

Assumptions in relation to the maximum technical pathway

Max Tech pathway: A combination of carbon abatement options and savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side. Options selected in Max Tech take into account barriers to deployment but are not excluded based on these grounds. Where there is a choice between one option or another, the easier or cheaper option is chosen or two alternative Max Tech pathways are developed.

The following assumptions apply:

1. Technology Readiness Level (TRL): process or technology at least demonstrated at a pilot scale today, even if that is in a different sector.
2. Other disruptive technology options that could make a significant difference but that are not mature enough for inclusion in the pathways are covered in the commentary.
3. Cost is not a constraint: it has been assumed that there are strong and growing financial incentives to decarbonise which mean that the cost of doing so is not generally a barrier.
4. Option deployment rate: the sector team followed the roadmap method process to develop and test option deployments in all pathways, including Max Tech. Hence, in each sector, rates at which the options can be deployed were considered as 'highly ambitious but also reasonably foreseeable'.
5. Biomass: maximum penetration of biogenic material as fuel or feedstock assuming unlimited availability. Carbon intensity and sensitivities are included in each sector.
6. Carbon Capture: All sectors have made individual (sector) assessments of the maximum possible potential by 2050 based on what is 'highly ambitious but also reasonably foreseeable'. This assessment included the most suitable CO_2 capture technology or technologies for application in the sector, the existing location of the sites relative to each other and anticipated future CC infrastructure, the space constraints on sites, the potential viability of relocation, the scale of the potential CO_2 captured and potential viability of both CO_2 utilisation and CO_2 storage of the captured CO_2.
7. Electricity Grid: three decarbonisation grid trends were applied through the scenario analysis.

Option Interaction Calculation

The pathway model incorporated two methods of evaluating potential interaction of options. The first method reflected the assumption that all options interacted maximally, and the second method reflected the assumption that the options did not interact. Neither of these cases was likely to be representative of reality; however the actual pathway trend would lie between the two. The two methods therefore provided a theoretical bound on the uncertainty of this type of interaction in results that was introduced by the choice of a top down modelling approach. Figures calculated based on the assumption of maximum interaction are presented exclusively in the report unless otherwise stated.

Cumulative Emissions

An important aspect of an emission pathway is the total emission resulting from it. The pathways presented in this report are not designed or compared on the basis of cumulative emissions over the course to 2050. Only end-targets are assessed e.g., it is possible for a pathway of lower 2050 emission to have larger cumulative emissions, and thus a greater impact on the global climate system. The exception to this is in the cost analysis section where total CO_2 abated under each pathway – as calculated by the model – is quoted.

Scope of Emissions Considered

Only emissions from production or manufacturing sites were included in scope (from combustion of fuels, process emissions and indirect emissions from imported electricity). Consumed and embedded emissions were outside the scope of this project.

Complexity of the Model

The model provided a simplified top down representation of the sector to which decarbonisation options were applied. It does not include any optimisation algorithm to automatically identify a least cost or optimal pathway.

Material Efficiency

Demand reduction through material efficiency was outside the scope of the quantitative analysis. It is included in the conclusions as material efficiency opportunities are considered to be significant in terms of the long-term reduction of industrial emissions: see for example Allwood et al. (2012) and the ongoing work of the UK INDEMAND Centre.

Base Year (2012)

The Climate Change Act established a legally binding target to reduce the UK's greenhouse gas emissions by at least 80% below base year (1990) levels by 2050. DECC's 2011 Carbon Plan set out how the UK will achieve decarbonisation within the framework of the carbon budgets and policy objectives: to make the transition to a low-carbon economy while maintaining energy security and minimising costs to consumers. The Carbon Plan proposed that decarbonising the UK economy 'could require a reduction in overall industry emissions of up to 70% by 2050' (against 2009 emissions).

In this project for the analytical work, we have set 2012 as the base year. This is the most recent dataset available to the project, and was considered to be a suitable date to assess how sectors (as they currently are) can reduce emissions to 2050. This separates the illustrative pathways exercise from national targets, which are based on 1990 emissions.

2.2.3 Conclusions and Next Steps

The conclusions and potential next steps are drawn from the outcomes of the pathways modelling, the scenario testing and the potential actions to overcome barriers and enhance enablers that were identified together with stakeholders. The strategic conclusions can include high-level and/or longer term issues, or more specific, discrete example actions which can lead to tangible benefits. The potential next steps are presented in the context of eight strategic conclusions (or themes) and six or seven technology groups. The strategic conclusions or themes are:

- Strategy, leadership and organisation
- Business case barriers
- Future energy costs, energy supply security, market structure and competition
- Industrial energy policy context
- Life-cycle accounting
- Value chain collaboration
- Research, development and demonstration
- People and skills

The main technology groups as presented in section 5 are:

- Electricity grid decarbonisation

- Electrification of heat
- Fuel and feedstock availability (including biomass)
- Energy efficiency and heat recovery
- Clustering
- Carbon capture
- Sector-specific technologies

3. FINDINGS

3.1 Key Points

For the UK the CO_2 emissions in 2012 from glass production totalled 2.2 million tonnes of CO_2 for a production of more than 3 million tonnes of glass products (British Glass, 2014). Direct emissions originate largely from fossil fuel combustion and raw material degradation in the furnace (process emissions), and indirect emissions from electricity from the grid, with the melting furnace accounting for about three quarters of all energy use in a typical UK glass plant. The energy use in the sector is dominated by natural gas (81%). Electricity use is 13% and other fossil fuels make up 6% (British Glass, 2014).

The UK sector can be divided into subsectors manufacturing container glass, flat glass, and fibre and domestic or speciality glass. Production of container and flat glass accounts for 95% of all glass production Ricardo AEA, 2013.

Between 1979 and 2008, furnace energy efficiency has been improved by 54% (Envirowise, 2008). However, post-1996 the improvements slowed down dramatically. Energy efficiency is perceived as important, but decarbonisation is generally not a priority in the current investment climate as it is currently perceived as additional business cost.

The views of the sector is that increased competition from other countries with, what are perceived to be, lower environmental regulations and energy costs is perceived to be making it more challenging for UK glass companies to remain competitive and obtain internal funding for investment across the sector, due to a reduction in profits, and investments going to other countries rather than the UK.

The UK glass sector has developed a decarbonisation roadmap, which sets out a clear vision and qualitative objectives for increased research into decarbonisation and specific work streams on decarbonisation. This demonstrates that decarbonisation is becoming a more prominent issue for the sector.

The main enablers for decarbonisation for the glass sector are:

- Technological and financial feasibility
- Strong recycling infrastructure
- High and increasing energy prices
- Increasing lifespan of equipment
- Replacement of obsolete equipment
- Alternative financing and access to capital
- Customer demand for more sustainable products
- Commitment by top management to an environmental policy or climate change strategy
- Policy Certainty
- Regulations encouraging energy efficiency in downstream sectors
- Legislative compliance
- High carbon price

The main barriers that hamper decarbonisation are:

- Long payback periods and high costs
- Lack of capital
- Insufficient quantities of high-quality cullet
- High and fluctuating energy prices

- Uneven playing field with overseas competition
- Chemical and process efficiency limitations
- Long plant life or investment cycle
- Difficulty to find external financing
- Risk of production disruption, hassle and inconvenience
- Low demand risk

The detailed enablers and barriers are discussed in section 3.4.5.

Future production for the UK glass sector is projected to grow somewhat, but a differentiation is made between container and flat glass. British Glass has the provided the following growth projections used in the analysis. Depending on the scenario, the container glass subsector is expected to decline or grow by -0.5%, 0% and 1% by volume for the challenging world, current trends and collaborative growth scenarios, respectively. The flat glass subsector is expected to decline or grow by -1%, 3.7% then 0%, and 3.7% then 1% by volume for the challenging world, current trends and collaborative growth scenarios, respectively. The sector's growth is reliant on trends downstream such as construction (e.g. high-efficiency glass for windows), automotive (e.g. light-weight glass for vehicles), beverage (e.g. clear versus coloured glass, heavy versus light-weight bottles), and fruit and vegetable processing producers.

The energy-saving and carbon-reduction opportunities for the glass sector distilled from the literature review, interviews, survey and workshops can be classified into eight categories: Raw Materials (including recycled glass), Furnace, Improved Process Control, Waste Heat Recovery, Fuel Switching, Carbon Capture, General Utilities and Product Design.

3.2 Glass Manufacturing

Glass is a combination of sand and other minerals melted together at very high temperatures to form a material that is ideal for a wide range of applications, from packaging and construction to fibre optics. Many different types of glass with different chemical and physical properties exist, and glass is 100% recyclable and can be recycled an infinite number of times without degradation in quality, strength or functionality. However, the main issue with infinite recycling is the quality of the available cullet. High-quality cullet requires colour separation and contaminations removal so that each grade of glass utilises appropriate cullet, requiring colour separation technologies and better recycling infrastructures.

In the glass sector, the following subsectors can be distinguished: container glass (bottles and jars), flat glass (windows for construction and automotive), domestic glass (tumblers, wine glasses and decorative glass), glass fibre (building insulation, glass wool, textile, reinforcement of plastics), optical fibre (optic cables for telecommunication), glass tubing (scientific instruments and lighting), and lamp and light bulb manufacture. The UK glass sector mainly produces container (65%) and flat glass (30%), with fibre glass (5%) only accounting for a limited amount of production (British Glass, 2014). Also, full data on the fibre sector was not available. It was therefore decided by the sector team to focus on container and flat glass only for the quantitative analysis of decarbonisation options and the development of pathways and next steps, and to cover fibre glass qualitatively.

3.2.1 Glass Manufacturing Processes

Glass manufacturing highly depends on the final product, but all manufacturing processes have a common origin: glass first needs to be melted. Glass melting requires raw materials (different types of sand and minerals or recycled glass), mixed together and charged in a furnace where they are melted at ca. 1,500°C. The molten glass is then taken out of the furnace to be shaped and cooled down, possibly further processed to have specific properties. During this manufacturing process, CO_2 emissions arise from the combustion of fossil fuels (natural gas or oil) in the furnace, and by the chemical decomposition of carbonate components in the raw materials (British Glass, 2014).

Figure 4 shows the container manufacturing process, but the generic stages are similar for all large-scale glass manufacturing processes (British Glass, 2014).

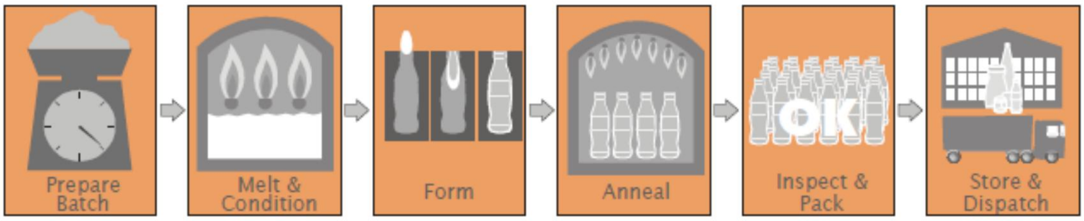

Figure 4: Stages in the container glass manufacturing process (British Glass, 2014)

The basic large-scale manufacturing process of glass consists of batch preparation, melting and conditioning, forming, annealing, inspection and packing, and storing and dispatch (Carbon Trust - GTS, 2004).

During **batch preparation**, the major relatively pure raw materials (typically 60% silica sand, 21% sodium carbonate and 19% limestone for container glass production) are carefully mixed (proportions depending on end-product) together with some additives to bring colour or improved chemical and physical properties. Recycled glass or cullet (internal = in factory returns, external = from recycling and separation sites or from old bottle collection), is also added in the melt (British Glass, 2014).

In the **glass melting and conditioning** stage, the raw materials and cullet are fed into the furnace (typically gas-fired direct heating), which is basically a refractory box-like structure operating at temperatures up to 1,700°C. Once melted, the batch material must be allowed to thoroughly mix and allow any gas bubbles to rise and escape, taking about 16 hours. Leaving the furnace, the batch enters the **glass forming** stage of the process, which is product-specific (British Glass, 2014).

Container glass production is achieved by streaming the molten glass down several feeder channels which lead to the glass forming machines (blow and blow, or press and blow), operating at 1,050-1,200°C. The glass drops through a hole at the end of these forehearths and is then redirected into a series of iron moulds. Compressed air blows the glass to the required shape (British Glass, 2014).

For **flat glass production**, the glass is formed into a single continuous ribbon by floating it on a bath of molten tin (electric direct heating), producing sheets with a perfect surface finish. Melting, refining (i.e. removal of impurities) and homogenising (i.e. creating uniform composition throughout the glass) take place simultaneously in the furnace, which is heated to 1,500°C. These different processes occur in separate zones in the complex glass flow driven by high temperatures (up to 1,700°C for refining), delivering the glass at 1,100°C to the float bath, free from inclusions and bubbles. Glass from the melter then flows gently over a refractory spout on to the mirror-like surface of molten tin, starting at 1,100°C and leaving the float bath as a solid ribbon at 600°C (British Glass, 2014).

Continuous filament fibre glass is produced by drawing the glass through an electrically heated bushing (1,200°C) containing many hundreds of tiny holes to form continuous flexible fibres that are drawn onto drums and used for textile type applications (British Glass, 2014).

Insulating fibre glass is produced by using centrifugal forces to thrust the glass through a rotating cylinder (spinner) with many thousands of holes. The fibres are then cut to size using compressed air knives to form short fibres which then fall onto a moving conveyor and are bonded together using organic binder to form a mat for insulation products (British Glass, 2014).

Once formed, all the different glass types can be **coated** to add additional properties (generally by spray-coating). In the forming process, very rapid temperature changes are encountered, inducing severe internal stresses within the glass. To remove these stresses, the glass goes through the process of **annealing**, which involves re-heating (400-600°C) the glass followed by a controlled cooling cycle. Annealing is generally performed continuously with the glass on a conveyor belt being fed through a long tunnel kiln or lehr (gas-fired or electric direct heating), and can take up to 40 minutes depending on the thickness of the glass. In the last phase of production, glass passes through a highly-automated **inspection** (up to 10 different checks), before it can leave the factory. Packing and dispatch are also highly automated (Envirowise, 2008).

Many innovations in industrial glass manufacturing have been explored during the second half of the 20th century, looking to solve critical industry problems. However, only a few of these innovations have been commercialised. Instead, the design of the furnace dating from 1867 has steadily evolved to meet the basic requirements for glass production, with minimal financial or technological risks. The need for advanced technologies therefore remains crucial for the future of glass manufacturing (Ross and Tincher, 2004).

3.2.2 Technologies for Delivering Heat and Power

The melting furnace is heated by burners, which are generally fired by natural gas, but occasionally they could also be fired by oil (stand-by fuel). Traditional burners are air-fuel fired, but an increased use of oxygen will increase fuel efficiency and reduce NO_x emissions. Air can therefore be enriched with oxygen, or burners can be 100% oxygen-fuel fired. However, the additional energy required to make oxygen must be included in emissions calculations. To increase energy efficiency, furnaces today are equipped with regenerators for primary heat recovery which pre-heat air. Secondary waste heat recovery van be installed to generate electricity, to pre-heat batch and cullet, and to generate steam in a waste-heat recovery boiler (e.g. for space heating). When plants are located in built-up and established industrial areas, there is also potential for ‘over the fence’ heat recovery for district heating (Ricardo AEA, 2013).

Combustion of natural gas is also used to provide the heat required in lehrs (annealing kilns) and in container glass forehearths. Electrical heating is used for flat glass float baths, and sometimes also for the lehrs. The majority of electricity used in the UK glass industry is currently supplied from the national electricity grid, although a very small amount of on-site generation from CHP or private wire supply is available too.

3.3 Current Emissions and Energy Use - Principal Question 1

This section covers the findings in response to principal question 1: ‘What are the current emissions from each sector and how is energy used?’ It focuses on technologies that are currently used in the sector, the emissions associated with the activities, the heat and power demand of glass plants and the fuels that are used to deliver this energy and the lifespan of equipment and key timings for replacement or rebuild.

3.3.1 Evolution of emission reductions

An efficient large furnace will require 1.4 MWh of energy per tonne of glass melted, hence a 300 tonne per day furnace will consume around 32,000 m^3 of natural gas each day (British Glass, 2014) and thereby releases some 62 tonnes of CO_2 per day (Carbon Trust - GTS, 2004). Larger furnaces tend to have higher efficiencies. Between 1979 and 2003 the average furnace specific energy consumption has improved from 3.2 MWh per tonne to 1.4 MWh per tonne (gross basis) by implementing state-of-the-art technology (SAT) improvements (Carbon Trust, 2005). Between 1979 and 2008, furnace energy efficiency has been improved by 54% (Envirowise, 2008). However, post-1996 the improvements slowed down dramatically. Table 4 below illustrates some of the areas and actions already implemented by the UK glass sector to reduce their emissions.

Area	Actions by the UK Glass Sector
Furnaces	• Companies have invested significant amounts of money to improve the energy efficiency of furnaces each time they are rebuilt, and • Efficiency has improved by more than 54% since 1979 (data measured in container furnaces) mainly due to advances in refractories (Carbon Trust, 2005).
Use of recycled glass	• Glass companies are working actively to increase closed loop glass recycling in the UK. Some have even built and operate recycling factories, and • Over 1 million tonnes of glass was recycled back to glass in the UK in 2012.
General utilities	• Companies have already implemented activities such as installing energy efficient lighting and variable speed drives. This is an area of ongoing improvements.
Process control	• Companies have already implemented process control, e.g. sub-metering and dedicated software. This is an area of ongoing improvements.
Waste heat recovery	• Some space heating using waste heat and other site specific measures have been implemented, and • Feasibility studies have been conducted into other uses for waste heat recovery including electricity generation and district heating.
Product design	• The container glass subsector has developed 'light weight' bottles. These require less energy to produce each bottle at the plant and less energy to transport, • The flat glass subsector has developed and invested in machinery to create light weight windscreens and coated glass for highly energy efficient windows. Energy efficient windows actually save more energy than was required to produce the glass, resulting in a carbon negative product, and • Fibre glass is a key component of wind turbines and light weight vehicle parts.
Renewable generation	• Feasibility studies have been conducted

Table 4: Emissions reduction activities

3.3.2 Emissions

The **UK** Glass industry produces more than 3 million tonnes of glass annually, with an estimated 2.2 million tonnes of CO_2 (British Glass, 2012) released by fossil fuel combustion (58%), process emissions (from raw material degradation) in the furnace (18%) and primary electricity generation (24%) (British Glass, 2014). The UK sector can be divided into subsectors manufacturing container glass (65% by weight), flat glass (30%), and fibre and domestic or speciality glass (5%) (Ricardo AEA, 2013).

The **container glass** (mainly bottles and jars) subsector is the largest of the UK glass sector. In 2010, it comprised 6 manufacturers producing a total of 2.3 million tonnes of glass. They operate 29 furnaces on 12 sites, with furnace capacities ranging from less than 100 to more than 600 tonnes of glass per day (Envirowise, 2008). The annual fuel derived emissions from these furnaces are approximately 650,000 tonnes of CO_2 per year. Additional CO_2 is released from the actual glass making process: for each tonne of glass produced from virgin raw materials, 185 kg of CO_2 is produced (Carbon Trust - GTS, 2004). Also, CO_2 emissions result from the generation of electricity used in the process. The **flat glass** industry (building and automotive glass) represents the second largest sector, with 3 companies producing 1.3 million tonnes in 2010. They currently operate 4 furnaces on 5 sites (some furnaces have been placed on hold), with furnace capacities ranging from 600 to 800 tonnes per day (British Glass 2014). The **fibre glass** industry comprises 3 insulation fibre glass manufacturers in the UK, operating at 4 sites, and 1 continuous filament glass fibre plant (Envirowise, 2008). The UK container and flat glass companies and their structure, activities and total emissions are shown in Table 5 below. This table excludes fibre glass, as this sub-sector was excluded from the quantitative scope of this project.

COMPANY	SUBSECTOR	# SITES	# FURNACES	TOTAL EMISSIONS
Allied Glass Containers Ardagh Glass Beatson Clark Encirc O-I Manufacturing Stölzle Flacconage Ltd	container	12	31 (29 currently operational)	1,558,909 tonnes CO_2
Guardian Industries NSG /Pilkington Group Saint Gobain Glass	Flat	5	7 (4 currently operational)	620,139 tonnes CO_2

Table 5: UK glass companies in 2014 (British Glass, 2014)

The specific energy consumption and specific CO_2 emissions for the main heat consuming processes are shown in Table 6. The unit of throughput is in terms of tonnes of product emerging from the process: in units of tonnes of glass melted for the melting process, and in units of tonnes of final product for downstream processes (DECC, 2014). From this table it is clear that melting is the most energy and CO_2 intensive process in the UK glass industry.

Direct heat consuming process	Specific energy consumption (MWh/tonne glass)	Specific CO_2 emissions (tonne CO_2/tonne glass)
Melting (all subsectors)	1.621	0.334
Forehearth (container)	0.085	0.018
Lehr (container)	0.085	0.018
Float bath (flat)	0.248	0.050
Forming (other	0.161	0.030

Table 6: Specific energy and CO_2 consumption in the UK glass sector (DECC, 2014)

3.3.3 Heat and Power Demand

In the UK glass sector, about 85% of all the fuel is used to generate heat, which is directly supplied to the process. Annually, approximately 6,000 GWh is used for melting (in all subsectors), 192 GWh in the forehearth (for container glass), 192 GWh in the lehr (for container glass), 180 GWh in the float bath (for flat glass), and 15 GWh in forming (other), resulting in a total heat demand of 6,500 GWh/year (DECC, 2014). Overall energy consumption in the UK glass sector (excluding fibre) is split to approximately 70% for container glass and 30% for flat glass production (British Glass, 2014). Data for fibre glass is excluded here, as this sub-sector was excluded from the quantitative scope of this project.

Melting furnaces are the major energy users in the glass manufacturing process, employing direct combustion heat (with air-fuel or oxy-fuel burners) possibly combined with electric boosting. Melting furnaces may account for over 75% of the total energy requirements in the factory, and are hence the most important areas for energy improvements, followed by refining and conditioning (Institute for Industrial Productivity, 2014). Other significant gas users within a glass manufacturing plant are the forehearths and the lehrs. Waste heat in furnace exhaust gases is generally recovered from the firing process using regenerators, capturing approximately 50% of the heat which is used to pre-heat combustion air or for other applications.

The largest users of electricity in a container glass plant - after the furnaces - are the compressors used to provide air for the glass-forming processes, the many fans used to cool the glass-forming machines and certain parts of the furnace (Carbon Trust, 2005). Other electricity users are pumps, bag-filtration to remove particulate pollution from exhaust gases, motors, electric lehrs, conveyors, packaging, laminating and glass coating equipment (ECOFYS, 2014).

The heat, power and cooling demand may change in the future due to trends in market behaviour, technological developments and regulation.

3.3.4 Fuels Used

Glass melting is a high-temperature and energy intensive operation with natural gas being the industry's principal source of energy. Since 2003, all furnaces in mainland UK were fired with natural gas. The gas distribution network did not extend to the single plant located in Northern Ireland and thus its two furnaces were fired with heavy fuel oil. Today, most furnaces are fired with natural gas (91%), but oil can be used as a standby fuel (6%), as illustrated in Figure 5. A number of other fossil fuels such as medium fuel oil form a minor part of the fuel mix. Forehearths are generally heated by natural gas (85%) with the balance of heat provided by electricity (15%) consumed in resistive heaters or electrodes. Heat for lehrs is generated by natural gas (70%) and electricity (30%) as radiant heaters. The refractory lined baths for the production of flat glass are normally heated by electric radiant heaters, but natural gas can be used if the electric radiant burners cease to operate. Heat for forming is provided in the form of electricity. Currently, no renewable and low-carbon fuels are used in the UK glass sector (DECC, 2014).

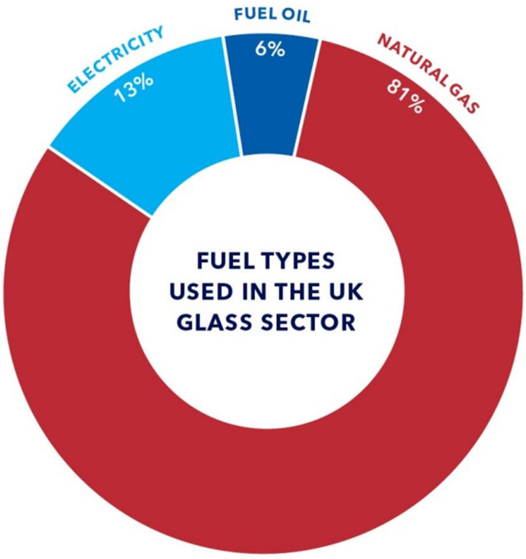

Figure 5: 2014 distribution of fuel type use in the UK glass industry (DECC, 2014)

3.3.5 Lifespan of Equipment and Key Timings

The production of glass takes place in furnaces that are constructed to continuously melt large quantities of glass over extended campaigns of 10-15 years (Ricardo AEA, 2013) for container glass. Flat glass furnaces, however, have a campaign life of approximately 20 years, after which they undergo a partial rebuild. Typically, after two campaigns a furnace is completely rebuilt. Since the furnace is the dominant energy centre in the factory, it represents by far the greatest opportunity for decarbonisation of the glass making process and is therefore determinative in setting the lifespan of the plants (British Glass, 2014).

CO_2 abatement opportunities will have to avoid interrupting the melting campaign and associated down-time and production losses. Disruptive changes such as renovating furnaces and introducing some other decarbonising technologies hence has to wait for the melting campaigns to end. The implementation of opportunities requiring retrofit will either have to wait until furnace rebuild or during unplanned down-time and lost production.

In conclusion, glass plants operate continuously and have long life cycles of up to 20 years. Not all decarbonisation measures need to be delayed until complete rebuild but can be temporarily bypassed on existing furnaces, but opportunities to finance large-scale disruptive technologies are at specific times, with 2 opportunities per furnace prior to 2050. The specific refurbishment dates for each furnace have not been identified because this information is commercially confidential; however, these dates are planned well in advance by the companies, so they can make plans to implement major decarbonisation opportunities at these times.

3.4 Business Environment - Principal Question 2

This section provides an assessment of the range of questions under principal question 2: 'For each sector, what is the business environment, what are the business strategies of companies, and how do these have an impact on decisions to invest in decarbonisation?'

3.4.1 Market Structure

The UK glass industry is a mature market, with high capital intensity requirements. It is a highly concentrated industry. IBIS (2013) found that it is dependent on trends in downstream construction (high-efficiency glass for windows), automotive (light-weight glass for vehicles), beverage (clear versus coloured glass, heavy versus light-weight bottles), and fruit and vegetable processing producers.

UK glass revenues were £853.4 million for container glass and £316 million for flat glass in 2013 (IBIS, 2013). Table 7 and Table 8 below provide details of the market share. The UK only has one continuous filament fibre glass producer, PPG.

Container Glass Manufacturers	%
Ardagh glass	36.1
O-I Manufacturing UK Ltd	11.5
Quinn Glass Ltd 26.8%	26.8
Allied Glass Containers Ltd	12.4
Stölzle Flaconnage Ltd	8.1

Table 7: Market share for container glass manufacturers (IBIS, 2013)

Flat Glass Manufacturers	%
Guardian Industries UK Ltd.	22.4
Saint Gobain Glass UK	23.4
Pilkington Group has	49.2

Table 8: Market share for flat glass manufacturers (IBIS, 2013)

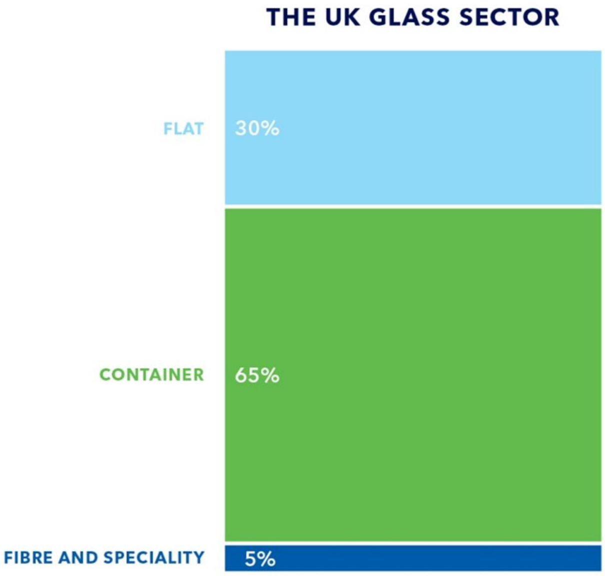

Figure 6: The UK glass sector (British Glass, 2014)

There are 459 flat glass and 53 container glass establishments (IBIS, 2013). An establishment is defined as the smallest type of accounting unit or physical location where business is conducted.

During the recession, due to the depression of the construction industry, demand for flat glass fell sharply. The economic recovery is seeing an increase in the demand for flat glass with British Glass (2014) advising that 3.7% annual volume growth anticipated between 2014 and 2019. Flat glass manufacturers expect that there may be strong growth in the next few years and then a stabilisation of demand. Key drivers for growth include demand from building and construction, automotive, and food and beverage packagers and retailers. The long-term growth prospects for the container glass industry hinges on the capability of bottle and jar manufacturers to compete against alternative packaging materials. The growth prospects for flat glass depend on the sector's ability to compete with import competition, and expanding into downstream shaped and processed flat glass products. The growth of the wind energy market, electronics, and bathroom industries will directly impact on the growth prospects of fibre glass in the UK.

In the production of container glass, cullet is added to the melt, giving significant energy savings and other benefits. However, from the perspective of CO_2 emissions, the greatest benefit results from the fact that remelting cullet does not result in 'process' CO_2 emissions, as is the case when fresh raw materials are used for glassmaking. The reduction in CO_2 emissions from lower process emissions is much greater than the emissions reduction associated with the energy savings resulting from the use of cullet. Cullet can arise within the factory as a result from breakage or rejected ware (domestic cullet), having the advantage of an identical composition to the glass being melted. Typically, a container glass plant rejects about 10% of its output and recycles it back as domestic cullet. The cullet can also be brought into the factory from external sources (foreign cullet), which is now a major source of raw material. Some green glass furnaces even operate at cullet levels in excess of 90% (Carbon Trust, 2005). Clear glass has the largest production market share in the UK, being the preferred colour for the food and drink sector, with a share of 64% (and 18% green, 17% amber, 1% other (British Glass, 2014). A lot of this clear glass is, however, exported and the largest UK market share regarding consumption is that of green glass (due e.g. to imports of green glass wine bottles). Therefore, more green than clear cullet is available in the UK, limiting the potential of cullet use for clear glass production.

Recycling in the UK is covered by several pieces of legislation, which provides the main driver for recovery of waste glass. About 50% of waste glass generated in the UK is recycled, whereas recycling rates of 60% (France), 77% (Netherlands), 81% (Ireland), 89% (Germany), and even 91% (Belgium) are achieved in the rest of the EU (Envirowise, 2008). The recycling industry comprises the collecting organisations and the cullet processors. Processors sort the glass to remove unwanted materials (metals, stones, paper, plastics, etc.). Glass destined for re-melting at container plants additionally undergoes some colour separation. Glass recycling is aided by the bottle bank system (glass collection points) which incorporates colour segregation. Availability of recycled glass depends on bottle banks, kerbside collection, other waste separation processes, and glass collected via the drinks trade from pubs and clubs.

Sales figures from the IBIS (2014) reports in Table 9 below were sent to the glass companies for comment through British Glass. Some container glass companies responded and predicted that the growth in sales revenue was reasonable, but advised that growth in sales does not mean an increase in tonnes of glass produced, because of the increasing number of lightweight bottles being manufactured in the UK.

For flat glass, British Glass did not receive any comments on growth rates as this was considered highly confidential. However, they advised the following based on engagement with the flat glass manufacturers. Demand is still lower than it used to be before the recession, but the construction market is now returning slowly to growth. Experian (2014) estimates that the construction industry grew by 6.2% in 2014 and forecast 14.3% growth by the end of 2017. As the economy recovers, the construction industry should recover, and hence flat glass demand should increase. Flat glass manufacturers expect that there may be strong growth in the next few years. There will always be a certain amount of ‘maintenance’ of the existing building stock, e.g. replacing windows and replacing old buildings with new and glass usage is more likely connected to construction technique (and fashion there-of) and activity in the economy. However, window replacement is not an area that attracts a cash incentive.

	Annual Growth in Sales Revenue 09-14	Annual Growth in Sales Revenue 14-19
Container glass manufacturing	0.2%	0.6%
Flat glass manufacturing	1.1%	3.7%
Flat glass shaping and processing	-1.2%	4.1%

Table 9: Sector sales growth data (Experian, 2014)

3.4.2 Business Strategies

In liaison with British Glass, DECC and BIS, eight face-to-face semi-structured interviews were carried out with British Glass (Technical Director and Chairman and CEO), Ardagh Glass, OI, PPG, Saint Gobain Glass and Pilkington which helped to inform our details on business strategy.

Existing Sector Plans. The UK glass sector has developed a decarbonisation plan in the form of a sector roadmap, which sets out a clear vision and qualitative objectives for increased research into decarbonisation and specific work streams on decarbonisation.

The UK glass sector is yet to set itself an overall quantitative reduction target by 2050. The UK sector engages with the wider European sector through British Glass representatives at the European Commission’s Environmental Committee and Task Force, engagement with Glass Alliance, and other industry associations. Although there are platforms available to glass manufacturers for discussing their views on decarbonisation, there were limited examples of collaboration on any demonstration or pilot projects due to high levels of competition and perception that Competition Law prevents collaboration on energy efficiency.

There were examples in the workshop and interviews of collaboration between suppliers of technology and glass manufactures or customers and glass manufacturers.

Interviewees and workshop participants attributed this to the high level of competition in the sector and manufacturers' perception that collaboration on an advanced technology would reduce their competitive advantage and concerns over costs and technical knowledge and skills in areas such as CCS/U. If the sector wants to move forward on the existing roadmap and progress disruptive technologies, greater collaboration is needed. Further research into providing safe collaboration platforms for glass manufacturers may be useful. Larger operators could consider collaboration within their organisation but between sites to create efficiencies.

The Business Environment. The interviews, literature review, and workshop participants indicated that the business environment is improving as downstream companies recover from the economic recession. Similar to other building materials sectors such as iron and steel, the economic downturn in the glass sector mainly impacted the flat and fibre subsectors due to the recession's negative impact on the building and construction sector. Container glass was only partially hit by the recession limiting revenues and profits. However, the container sector faces increasing competition from alternative materials.

The senior decision maker at a glass manufacturing association stated his opinion: that for container glass "*Glass manufacturers have lost out in the UK in comparison to Europe. Milk and vegetables market share has reduced to 20-21%. In other parts of Europe it's about 30%. It is holding steady, but the market share is not increasing*."

At the workshop, there were views that competition from Tetra Pak and plastic for juice has seen the UK market share decline. There were also views that increasing that perceived higher energy costs in the UK compared to European or international competition was also a key barrier and makes up a large proportion of operating costs. For container glass, reduced market share in the UK can be overcome by increasing sales of premium brands to emerging markets.

For example, Allied Glass (2014) publicly reports that: "*72% of Allied's sales by value are in the spirits sector, 80% of Scotch Whisky is exported globally, and Scotch Whisky sales growth is significant in emerging economies where premium branding is paramount.*"

If the sector as a whole can maintain its competitiveness against other materials and international competition, it will grow, enabling an improved business environment for investing in decarbonisation technologies.

Decarbonisation Strategies

British Glass has developed a 2050 decarbonisation roadmap, demonstrating that decarbonisation is becoming a more prominent issue for the sector. The survey results on business decision-making related to decarbonisation in Section 3.4.3 show that the majority of companies (16 out of 17 respondents) have carbon or energy reduction targets and decision-making processes in place in relation to energy reduction and carbon. The information sources found that energy efficiency is perceived to be more important than decarbonisation as it has a direct financial benefit in terms of energy cost. This was backed by both a workshop exercise, and the interviews. Management commitment to decarbonise and address climate change was seen as an enabler as often the decarbonisation journey is challenging and requires management buy-in. Energy efficiency helps reduce companies' operational costs through increasing the lifespan of the furnace and reducing exposure to fluctuating and increasing energy prices. In the container glass sector, climate change was perceived as a more strategic issue due to high levels of customer demand from leading food and beverage companies for more sustainable packaging. Increasing demand for more sustainable building materials from voluntary agreements, regulations, and for public housing is also increasing the importance of decarbonisation to flat glass manufacturers. Fibre glass companies are interested in decarbonisation from the lifecycle perspective as it helps with reputation and brand building by enabling fibre to highlight the positive impacts of their products' final application, such as in wind turbine manufacture.

All of the companies interviewed had either a climate change strategy or environmental policy in place. Two interviewees indicated that energy efficiency is not a new issue for them, and that glass companies have been investing in it for the last 50 years. All interviewees also had decarbonisation targets in place at group level, and site level energy efficiency targets or KPIs are closely monitored. This was reinforced by the survey results. When survey respondents were asked what their position was in regards to carbon and energy efficiency reduction, the majority of respondents considered themselves to be already implementing new decarbonisation technologies. However, innovation is seen as a competitive area in the glass sector, having a negative impact on and limiting collaborations for demonstration and pilot projects. Thus, participants are investing in energy efficiency projects, but often do not feel comfortable discussing or sharing information regarding these projects with other glass manufacturers. Moreover, participants recognised they could be doing more, but are often unable to due to high paybacks, lack of funds, and inability to collaborate with other manufactures on demonstration projects due to high levels of competition and energy efficiency being perceived as an area of competitive advantage. Figure 7 below shows the percentage of survey respondents who voted for a specific innovation descriptor.

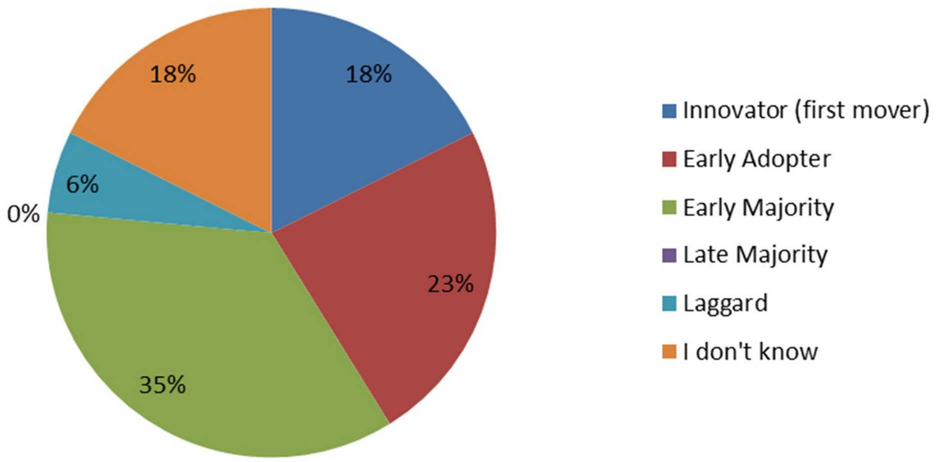

Figure 7: Attitudes to innovation

3.4.3 Decision-Making Processes

The interviews identified that decision-making processes vary by company and the most important factor in regards to the level of authority of investment expenditure includes size of the company and ownership structure. For large multinational companies there are decision-making hierarchies and expenditure thresholds that UK based leaders must abide by or seek additional approval from the Group if the project is above this level of expenditure. For example, limits to spend for one interviewee from a large multinational company were based on 1% of turnover mainly for repairs, improvements, and efficiency. Anything beyond this 1% threshold must be submitted to the Group. An interviewee from a medium sized multinational company also has clear financial decision-making hierarchies starting at the plant level, followed by the UK managing director, the global operating manager, the vice president, and for any projects in the millions these must be approved by the CEO and executive committee.

All companies interviewed used commercial and productivity criteria to inform their decision-making and indicated that project managers must come up with the business case for the project, and payback criteria under two or three years must be met in order for the project to move forward. Longer paybacks of four to five years are accepted if the project must be done to maintain manufacturing processes.

One interviewee, who was part of a smaller glass company, indicated that because it is leaner, it is able to make decisions quite quickly. Board members are all located in the same office, and as the Board is smaller in size, it is able to quickly change direction. The interviewee mentioned this also has additional benefits in regards to oversight of the implementation of projects, as they are easily able to closely monitor any new project's impacts on the furnaces and production levels, whereas decisions made outside of the UK by a Group leadership team may be more difficult to monitor. This may suggest smaller companies may have greater success with implementation, but more research would be needed to explore this further.

With regards to investing in retrofit projects, small companies are potentially less able to implement retrofits as the numbers of furnaces they have are limited and thus any retrofits could potentially significantly impact their production levels and revenues.

To conclude, decision-making within glass manufacturing is complex, and site level investment budgets for large multi-nationals may be limited by Group who determine the energy efficiency projects that can be invested. Smaller glass manufacturers may have less money available to invest, but are often able to make decisions more quickly and are able to monitor and implement decisions that have been made, potentially increasing their chances for success.

The survey results displayed in Table 10 below shows that the majority, 14 of the companies have energy efficiency and decarbonisation targets in place and 13 translate these into site level targets. 13 of respondents have systematic decision-making processes in place with regards to energy efficiency and decarbonisation and indicated energy efficiency and decarbonisation were tracked at management meetings. 14 of the respondents indicated that there are clear roles and responsibilities in place for decarbonisation. Overall, the survey results would indicate that carbon and energy reduction decision-making processes are well established. However, the interviews identified that for multi-national companies although decision-making processes are well established, decisions may take longer due to the various decision-making levels and hierarchies. The number of respondents was limited to 17 out of the 50 workshop participants due to limited time between when the survey was issued and when the workshop was held. The survey included those that were interviewed.

Question	Highlights of responses
1. Our organisation has well defined goals and objectives or targets on energy efficiency and decarbonisation.	14 of responders either agree or strongly agree
2. Our company goals and objectives get translated to targets at site level.	13 of responder either agree or strongly agree
3. We have a systematic decision-making process for new initiatives with regards to energy efficiency and decarbonisation that work well.	10 agree
4. We track progress of energy and carbon improvement projects in management meetings.	13 either agree or strongly agree
5. We have some specific roles or allocated responsibilities within the company with regards to energy efficiency or decarbonisation.	14 either agree or strongly agree
6. Our organisation has strong communication and information sharing channels that support the implementation of options with regards to energy efficiency and decarbonisation successfully.	10 agree

Question	Highlights of responses
7. We have understanding of which energy efficiency and decarbonisation technologies can be implemented in our organisation.	14 either agree or strongly agree
8. We have a sufficiently skilled workforce to implement and handle energy efficiency and decarbonisation technologies.	14 either agree or strongly agree

Table 10: Industry responses to energy efficiency and decarbonisation

Overall, the main considerations for advanced energy efficiency technologies are availability of capital to invest, competition for internal funds with other parts of the business or priorities, commercial risks, fear of disruption hassle and inconvenience, potential impact on productivity, ROI and cost savings. Although climate change policies are considered as part of the decision-making process, for the majority of companies interviewed, environmental and climate change benefits are not the primary criteria for decision-making.

3.4.4 Financing Investments

Companies are less likely to finance investments in decarbonisation if the payback period is greater than two years as investors and senior managers demand quick paybacks to minimise risk. This was reinforced by the survey results in which 13 of the 17 respondents indicated that payback is a significant barrier (4). Workshop participants also categorised this as a significant barrier (4) and all interviewees indicated payback was the most significant barrier. Another key barrier to financing disruptive technologies is the availability of capital, mainly due to competition for internal funds in multinational companies and other projects more closely related to the core business.

All interviewees indicated that they mainly finance advanced energy efficiency technologies through their own revenues, where the cost of capital is less compared to paying interest on loans, and so is preferable to obtaining bank finance. Although several interviewees had applied for external funding through government grant and schemes, they found the application processes were too bureaucratic and complex and not enough internal resources to be able to identify the funding available. At one of the workshop tables, it was discussed that British Glass could potentially help with identifying the funding and schemes available to glass manufacturers. The workshop, survey, and interviews indicated that third party financing would be a good way to overcome paybacks over 3 years. Interviewees mentioned they would invest in solar or wind turbines to generate electricity at their plants if a third party took on the upfront financial risk off the balance sheet of the glass company for the investment.

When asked if any barriers were missing from the list, one survey respondent (a senior manager at a glass manufacturing company) indicated that "*Glass is a low margin product and margins are too small to generate capital for investing in non-core technologies* [i.e. technologies not essential to the glassmaking process]. *Productivity and compliance technologies* [i.e. investing to maintain production or meet legislative requirements] *will always come first*."

When asked how this barrier could be overcome, workshop participants indicated that there may be an opportunity to collaborate and share the costs of demonstration projects; however, concerns regarding the collaborations impact on competitiveness would need to be addressed first.

Linked to payback is the fact that glass plants operate continuously and have long life cycles around 20 years. This means there are limited opportunities to finance large scale disruptive technologies prior to 2050.

3.4.5 Enablers and Barriers

One of the outcomes of the analysis of the sector is a list of the most prevalent enablers and barriers for decarbonisation. The enablers and barriers have been identified through a number of different research methods, namely literature review, interviews, survey and workshops. Triangulating data has been of utmost importance. Seen below are details of the enablers and barriers that have not only been triangulated with regards to research methods, but were also selected at the workshops as the most important enablers and barriers.

Table 11 and Table 12 below indicate the most prevalent enablers and barriers across literature and interviews, as well as the perceived level of impact to decarbonisation as assessed by survey respondents and workshop participants. Although the number of times an enabler or barrier was referenced or highlighted could provide some guidance as to the strength of sentiment towards a particular enabler or barrier, the discussions during workshops and interviews provided a greater understanding as to the detail and context behind each barrier and enabler.

- More than 85 documents reviewed as part of the literature review. The number in the literature column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of sources that discuss it.
- There were eight semi-structured interviews in total. The number in the interview column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of interviewees that discussed it.
- The survey column shows the impact level of the enabler and barrier as assessed by 17 survey respondents, predominantly management-level representatives of UK manufacturers.
- The workshop column shows the impact level of the enabler and barrier as discussed and agreed by the evidence-gathering workshop group.
- The numbers on the left-hand side do not present a ranking but provide an easy point of reference to the order of analysis.

These enablers and barriers are illustrated throughout the text with supporting quotes and citations from interviews, workshops and literature. Further depth and interpretation is provided in the following paragraphs.

Top Enablers

#	Category	Enablers	Primary Source	Prevalence in occurrence		Level of impact	
				Literature	Interviews	Workshop[11]	Survey
1	Financial Technology	Technological and financial feasibility	Literature	2	5	High to very high	High to very high
2	Infrastructure	Strong recycling infrastructure	Literature	1	2	High to very high	High to very high
3	Market Economy	High and increasing energy prices	Literature	2	3	High to very high	High to very high
4	Operational	Increasing lifespan of equipment	Interviews	0	2	Medium to high	Medium to high
5	Operational	Replacement of obsolete equipment	Literature	1	2	No impact	Medium to high
6	Financial	Alternative financing and access to capital	Literature	5	2	Limited to medium	High to very high
7	Value Chain	Customer demand for more sustainable products	Literature	2	6	Limited to medium	Medium to high
8	Management Organisation	Commitment by top management to environmental policy or climate change strategy	Literature	1	2	No impact	Medium to high
9	Legislation	Policy certainty	Interviews	0	4	Limited	Medium to high
10	Legislation	Regulations encouraging energy efficiency and taking into account lifecycle emissions.	Literature	1	2	Medium to high	Medium to high
11	Legislation	Legislative compliance	Interviews	1	1	Limited	Medium to high
12	Market Economy	High carbon price	Interviews	0	4	Limited	Limited to medium

Table 11: Top enablers

The first enabler –– **technological and financial feasibility** –- was identified by literature (Energetic, 2002 and Venmans, 2014) and surveys, and a key discussion point both in interviews and the workshops. If technology is proven and financially viable (less than 2 year payback), it is more likely to be deployed.

Across the information sources it was clear that technologies that have been successfully trialled previously and with payback periods under 2 years would more likely be implemented over others.

Workshop participants indicated that it was difficult to determine when something is proven and viable. Participants discussed that often it is enough for one plant to have demonstrated the technology prior to it being implemented and, indicated it is best to be the first follower.

Financial feasibility and payback periods are discussed in more detail as a barrier.

A senior manager from a glass manufacturing company stated: *"We will have to work with technology that is economically more viable than existing technology or even better."*

The second enabler – **strong recycling infrastructure** – was identified by literature (Energetics, 2002) surveys, and confirmed in a lengthy debate during the workshops and in the interviews. A strong recycling infrastructure produces high-quality cullet that is sorted by colour, which enables cullet recycling and reduces carbon emissions.

During the workshop, it was evident that there are differences in the quality requirements amongst the glass subsectors. Fibre glass is currently not recycled, flat glass requires the highest quality cullet followed by container glass. Interviewees and workshop participants expressed a preference for a return to the bottle bank system, as a possible solution to the problem that current recycling system does not produce high enough quality cullet at an affordable cost, especially for clear glass which is also discussed as a barrier.

"The industry's top need is a cost-effective technology for sorting and separating post-consumer glass." (Energetics, 2002)

A director at a glass manufacturing association said: "*The best way to reduce emissions in the short term is to increase close loop recycling."*

The third enabler – **high and increasing energy prices** – was identified by literature (British Glass, 2014 and Venmans, 2014) and confirmed in three interviews, by the surveys and during the workshop, as a potential enabler. High energy prices enable the investments in energy efficiency technologies by potentially reducing the payback period on investment.

Across the information sources, it was highlighted that high energy costs can act as an enabler, but over a certain threshold the cost becomes too high and can act as a barrier in terms of its impact on overall competiveness of the sector. This is a very important factor across industry.

"The high cost of energy is a strong incentive for reducing energy use (and hence CO_2)." (British Glass, 2014)

The fourth enabler – **increasing lifespan of equipment** – was identified during the interviews and confirmed by the surveys and workshops. Increasing the lifespan of equipment may enable the investment in energy efficient technologies because equipment that lasts longer justifies larger investments. This is also discussed as a barrier due to fewer opportunities for use of new technologies.

The fifth enabler – **replacement of obsolete equipment** – was identified in literature (Venmans, 2014) but questioned during interviews and the workshop. As equipment becomes obsolete, more energy efficient technologies can be deployed.

Although the majority of survey respondents voted on replacement of obsolete equipment as having a high impact, the workshop and interviews felt that replacing old equipment is a normal part of business operations and cost savings, and is unlikely to lead to any radical step change in decarbonisation and the decarbonisation potential will be limited once efficiency limitations have been realised. Workshop participants indicated that this was not an enabler, but rather a standard procedure, and those replacements would not make the big difference for decarbonisation.

The sixth enabler – **alternative financing and access to capital** – was identified by literature (British Glass, 2014; TUC, 2012; Venmans, 2014 and Centre for Low-Carbon Futures, 2011) and confirmed by interviews, surveys and the workshop. Alternative financing like lease back schemes or government grants, Energy Companies Obligations funding or third party suppliers can help share costs and reduce risks of investments with longer payback periods. This is also discussed as a barrier where interviewees indicated they had difficulties identifying where to obtain outside financing, and that often application processes were complex.

"There are 10 comparatively large companies operating 18 sites across the UK. The Green Investment Bank's mandate can make a real, immediate contribution to securing funding for the technological innovations that could make the greatest difference to the EIIs, including lending to small- and medium-sized businesses with scope to innovate but currently facing real barriers to accessing capital." (TUC, 2012).

The seventh enabler – **customer demand for more sustainable products** – was identified by literature (Glass for Europe, 2014 and Gordon, 2008) and confirmed in six interviews, by the surveys and during the workshop, as a potential enabler. Customer demand for more sustainable products includes two types of products. The first is demand for products which have a lower carbon footprint in the manufacturing cycle such as like light-weight glass.

The second is demand for products which save more carbon during their lifetime such as triple glazing. Increasing customer demand for these products can drive innovation and investments.

Across the information sources, it was clear that glass products can help reduce lifetime emissions during end use. This can be through the use of fibre glass to create a wind turbine blade, triple glazed flat glass to reduce the lifetime emissions of a building or reduce the fuel requirements of a vehicle. Workshop participants discussed that builders get incentivised to increase energy efficiency when building a new house (double or triple glazing), but existing home owners or those renting houses do not.

The research highlighted that for container glass, UK customers have a high demand for light-weight bottles due to the presence of large multi-nationals who have comprehensive sustainability strategies. Workshop participants discussed that end consumers will generally choose the upfront low cost option without looking at energy efficiency.

There are differences between flat, fibre, and container glass when it comes to customer demand as the demand comes from different sectors which are under different regulatory and market pressures.

A director at a glass manufacturing company, said: said: *"Our customers in the UK are more interested in our sustainability credentials than others. We supply mainly multinationals, and they are more attuned. It is a hotter topic in UK as a result."*

"Glass can help contribute to zero-energy building stocks, greener vehicles and photovoltaic modules. The Dutch scientific institute TNO quantified that over 100 million tonnes of CO_2 could be saved annually if this were replaced with advanced glazing." (Glass for Europe, 2014)

The eighth enabler – **commitment by top management to environmental policy or climate change strategy** – was identified in literature (Venmans, 2014) and during the interviews, and confirmed by the surveys, but challenged during discussions at the workshop. This commitment enables top management to sign off on low-carbon technologies as they align with the company's strategies and policies.

Although workshop participants indicated that top management prioritise the bottom line over decarbonisation or climate change, the interviews and survey indicated that top management commitment to invest in risk energy efficiency projects and management commitment to an environmental policy or strategy is necessary to sign off on energy efficiency projects. This is especially the case in small companies, where the top executive makes the final decisions. Workshop participants indicated that top management wants to make money, and will do what Stakeholders want them to do. The main driver therefore is finance, not from a solely environmental perspective. One workshop participant indicated there is a reluctance of managers to tackle energy culture systematically.

"Enablers for investing in energy efficiency: Commitment by top management to an environmental policy." (Venmans, 2014)

The ninth enabler – **policy certainty** – was identified by four interviews and confirmed by the surveys, but questioned during the workshop. A stable energy efficiency and carbon regulatory framework enables investments in low-carbon energy by creating a stable investment environment.

The interviews highlighted that changes to policies in the past have caused a sense of uncertainty. For example reductions to the solar FIT tariff, the switch from revenue neutral to full purchase for CRC and delay to implementing zero carbon homes targets Whilst the UK government's commitment to 80% CO_2 reduction by 2050 had helped businesses to understand the long-term decarbonisation goals, it was still thought that policy certainty is not currently enabling investment but has potential to do so and as such was included as an enabler. Examples were of the electricity generation sector were discussed where the government has provided 'contracts for difference' which allows low-carbon investments to be made with relative certainty of return on investment.

A senior representative of a glass manufacturing association said: *"Policy certainty and level playing field with overseas competition are key enablers."*

The tenth enabler – **regulations encouraging energy efficiency and taking account of lifecycle emissions** – was identified by literature (Glass for Europe, 2014) and during the interviews, and confirmed both by surveys and the workshop. Such regulations create more demand for sustainable glass and therefore more revenues to invest in advanced technologies.

Across the information sources, regulations that could incentivise the sustainable use of glass and identify and apply a robust LCA methodology that rewards or takes account of 'glass' end use, and not just the emissions during its manufacture, would be a strong enabler to help reduce emissions overall and can help other sectors achieve their reductions such as the buildings and automotive sectors. Workshop participants indicated that if regulations take account life cycle emissions through LCA and are done correctly for products, this would stimulate product and process improvements. Participants discussed the opportunity for government to help spur the demand for more sustainable flat glass through zero carbon building requirements and the like. There are challenges to using LCA as it is complex: where the boundaries are drawn, and what methodology is used can change the results.

A senior manager at a glass manufacturing company stated: *"Government needs to take a lifecycle view on regulations."*

The eleventh enabler – **legislative compliance** – was identified in literature (Venmans, 2014) and by one interview, and was discussed during the workshop. When companies must meet government regulations, this is a driver for investment decisions.

Legislative compliance, and the costs and opportunities associated with it, was seen as potentially both an enabler (to legislate environmental standards required and maintain license to operate) and a barrier to decarbonisation (if costs of legislative compliance are too high and impact on competiveness). Workshop participants felt that whilst requirements for Industrial Emissions Directive (IED) meant that the various abatements were purchased, it was doubtful whether these actually achieved an overall environmental benefit (NO_x versus CO_2) and there was also a chance that, if costs were too high, closure may follow. Another workshop group indicated that there was a need for balance between regulatory compliance, and costs thereof, versus cost of moving abroad.

The twelfth enabler – **high cost of carbon** – was identified by four interviewees, but discussed in a lengthy debate during the workshops. EU ETS is a legal obligation for the glass sector. It creates a cost for emitting carbon, and hence aims to drive investments in energy efficiency and decarbonisation. The glass sector has been assessed to be at risk of carbon leakage, so glass installations currently receive some free allowances to mitigate against the cost of EU ETS compliance.

There is a separate tax called the carbon price support (CPS) mechanism, designed to provide a minimum floor for the price of carbon. However, because this is a UK-only policy, the increased costs on higher electricity prices for industry cannot be passed on to consumers, thereby increasing the risk that companies will go out of business or relocate abroad (carbon leakage).

Whilst some felt it was not a significant cost yet, future increases to the cost of carbon are expected due to EU ETS. This may become an enabler for decarbonisation, but it will also lead to increased costs and therefore be seen as a barrier in terms of competiveness if costs become too high compared to other countries outside the EU where glass is made.

A careful balance must always be sought between the overall price of carbon and the risk to industry of increasing costs. The risk and detailed impact of carbon leakage and carbon pricing is outside the scope of this work.

One interviewee, a senior manager from a glass manufacturing company, said: *"EU ETS carbon price: it's a cost but not a significant cost to us in terms of carbon price."*

Top Barriers

#	Category	Barriers	Primary Source	Prevalence in occurrence		Level of Impact	
				Literature	Interviews	Workshop [12]	Survey
1	Financial	Long payback periods and high costs, ROI too small	Interviews	1	7	High - very high	High - very high
2	Financial	Lack of capital	Literature	5	4	Limited - medium	High - very high
3	Infrastructure and Value Chain	Insufficient quantities of cullet and low quality of available cullet	Interviews	5	6	High - very high	High - very high
4	Market Economy	High and fluctuating energy prices	Interviews	1	7	Limited - medium	High - very high
5	Legislation	Uneven playing field with overseas competition	Interviews	1	6	High - very high	High - very high
6	Technology	Chemical and process efficiency limitations	Literature	1	1	High - very high	High - very high
7	Operational	Long plant life or investment cycle	Interviews	1	3	Medium - high	High - very high
8	Financial	Difficulty to find external financing	Workshop	2	2	Medium - high	Medium - high
9	Operational	Risk of production disruption, hassle and inconvenience	Literature	3	3	High - very high	Medium - high
10	Market Economy	Low demand risk	Workshop	1	0	Medium - high	Medium - high

Table 12: Top barriers

The first barrier –- **long payback periods and high costs** –- was identified in the literature (British Glass, 2014) and had been confirmed both by interviews, surveys and workshops. Long payback periods and small return on investment surpass companies' investment criteria, which typically require payback periods of less than 2 years. Technologies with longer payback periods are therefore less likely to be implemented.

A senior manager of a glass manufacturing company stated: *"ROI and payback period are crucial. It gets harder to justify smaller projects if it doesn't have a minimum of 2 year payback."*

"There are large barriers to implementing further measures and the biggest is often a lack of finance. There must be a strong, clear business incentive to make expensive, disruptive and risky decarbonisation changes." (British Glass, 2014)

[12] The numbers under Workshop represent the impact (-1 to 4 with -1 representing a negative impact and 4 representing a high positive impact) rather than the number of references or number of workshop votes. Impact levels were agreed by each table at the workshop.)

The second barrier –- **lack of capital** –- was identified by several literature sources (British Glass, 2014; TUC, 2012; Venmans, 2014 and Centre for Low-Carbon Future, 2011) and four interviews, and confirmed by surveys and workshop participants. A lack of capital will result in internal competition for funds.

Multi-national companies highlighted that it is difficult to obtain funds for UK energy efficiency projects, when there may be more profitable investments more closely aligned to the core business in other plant locations outside the UK. Interviews highlighted that RD&D funding has become more limited in size and number, or RD&D funding available is not earmarked for process efficiency innovations. The workshop and interviews indicated that in some instances there is no capital available, and in others, the capital is limited due to governance structure of the company or expenditure limited to a percentage of turnover.

The cost justification of energy efficiency projects over other projects was seen as an additional internal decision-making barrier. Workshop participants indicated that competition for capital can be separated out from lack of capital. Lack of capital is different for different companies: small companies may struggle with lack of capital. There is anecdotal evidence to suggest that there is a lack of finance with sufficiently attractive interest rates for environmental projects. Even Green Investment Bank loans are seen as too high interest by some.'

"Availability of capital: A large proportion of UK companies operating in the energy intensive sector are subsidiaries of global organisations. They compete internally for capital investment. Higher costs make it more difficult to justify internal group investment in the UK. The Green Investment Bank was, however, seen as potential source of capital for energy efficiency projects." (Centre for Low-carbon Futures, 2011).

The third barrier –- **insufficient quantities of cullet and low quality of existing cullet** –- was identified in the literature (EPA, 2008; Energetics, 2002 and Wood and Balhuizen, 2013, Ricardo AEA, 2013 and Butler, 2005) and was confirmed by interviews, surveys and the workshop. Glass is infinitely recyclable, and using cullet reduces emissions. One million tonnes of glass was melted back to glass in 2012. Lack of availability prevents more cullet being used for making into new glass (re-melt).

The current system does not produce enough high enough quality cullet to meet manufacturing needs, especially for clear glass. Interviewees and workshop participants highlighted a perceived need to return to the bottle bank system and increasing bottle returns may improve the amount of cullet, and as such as also been included as an enabler. Two interviewees also indicated they had invested in advanced sorting technologies for their suppliers or using special bags to backhaul flat glass from customer sites.

Participants indicated that there are differences in the quality requirements amongst the glass subsectors. Fibre glass is currently not recycled, flat glass requires the highest quality cullet followed by container glass.

A technical leader interviewed stated*: "The volume of cullet available to recycle: collection and distribution in cycle is not mature or deeply established across the demolition (usage) chain."*

"The availability of good quality cullet will determine the degree to which melting energy can be reduced further. While container glass melting may be more accepting of mixed recyclate, flat glass manufacture is far more exacting in the origin of cullet. Further increases in the use of cullet may require glass manufacturers to intervene in the glass recycling business in order to secure cullet of the required quality, and the author, through his communications with British Glass, is aware of one container glass manufacturer doing this. Availability of recycled glass of the required quality (including colour). Availability of clear cullet can be particularly problematic." (Ricardo AEA, 2013).

The fifth barrier –- **high and fluctuating energy prices** –- was identified by literature (Centre for Low-Carbon Futures, 2011) and confirmed in seven interviews, in the surveys and during workshop discussions. High and fluctuating energy prices make it difficult to calculate the return on investment on new technologies, and make some technologies such as electric melting cost-prohibitive.

All information sources highlighted that fluctuating energy prices make it difficult for glass manufacturers to plan the return on their investments, and are a major operational cost. Interviewees and workshop participants believed the electricity grid would become more decarbonised, but that the price of electricity is too high and thus does not encourage a switch to electric furnaces. Interviewees were concerned about UK's competitiveness in relation to Europe and other markets due to the higher energy prices in the UK. A recent publication of Agora – Energiewende (2014), however, illustrates that the comparison of electricity wholesale prices between sectors and countries is difficult. Moreover, a recent communication from the European Commission on energy prices and costs in Europe shows that UK electricity prices for industry are very similar to the average EU-27 prices, although certain countries (like Bulgaria and Finland) show significantly lower prices (European Commission, 2014).

As previously discussed, high energy prices can be perceived as an enabler as they could force companies to focus more on energy efficiency, but if energy prices get too high then production moves elsewhere.

"A number of representatives identified the high and rising costs of energy and energy taxes in the UK, as well as rising commodity prices, as a barrier to investment." (Centre for Low-Carbon Future, 2011)

"While numerous European companies have complained of market distortion due to regulatory favouritism for Germany's energy-intensive industries, caution must be exercised when attempting to directly compare industrial end-use prices between countries and sectors. Because firms in different regions and Sectors vary considerably in the extent to which they pay wholesale market prices and/or receive tax exemptions and levy reductions, comparing prices between Sectors and countries is a difficult task. The heterogeneity of the situation is not fully and transparently captured by European statistics." (Agora – Energiewende, 2014)

The sixth barrier – **uneven playing field with overseas competition** – was identified from the literature (Glass for Europe, 2014) and mentioned as a barrier from the industries point of view in seven interviews, the surveys and the workshop. The opinion of the industry is that there is an uneven playing field with overseas competition due to differences in climate change and energy policies impacting overall competiveness.

During the workshop it was noted that glass exemptions for EU ETS and the economic recession have limited the impact of carbon leakage on the sector. However, the views of interviewees and some workshop participants are that they are beginning to experience carbon leakage. The perception is that since 80% of large glass companies operating in the UK are owned overseas, investment has large potential to go elsewhere, such as Algeria and edges of Europe especially for automotive.

A director at a glass manufacturing company said: *"If they continue to charge us for CO_2 and we are competing with plants in Egypt, who don't have the costs of CO_2, we will move to Egypt. Carbon leakage outside the EU and outside the UK is an issue."*

A senior manager at a glass manufacturing company said: *"More on the Southern European front. We have seen a reduction in exports of glass. It impacts on exports before imports. The scheme currently misses the impact downstream. Using spirits, 80% of spirits are exported, mainly EU, North America and Asia. It will become more expensive to trade. If it isn't our exports it will be our customer's balance of trade. The term carbon leakage is narrowly defined within the EU ETS. You have to look at different levels."*

The seventh barrier – **chemical and process efficiency limitations** – was identified in the literature (Centre for Low-Carbon Futures, 2011) and was confirmed both by the interviews, surveys and workshop participants.

The interviews and workshop highlighted that the remaining glass manufacturers in the UK have been decarbonising and improving their energy efficiency over the last 50 years. It was the opinion of some participants in the workshop that manufacturers may have nearly reached the highest efficiency limits possible. However, better plant level efficiency data could help ascertain whether this is indeed the case.

> *"For many industries, much has already been done to improve the efficiency of the processes involved; there are efficiency limitations on current processes."* (Centre for Low-Carbon Futures, 2011)

The eighth barrier – **long plant life and investment cycle** – was identified in the literature (Ricardo AEA, 2013) and confirmed by three interviews, the surveys and during the workshop. A long plant life (typically 15-20 years) allows only limited opportunities to invest in major technological manufacturing changes and therefore limited opportunities to invest in an advanced technology that can significantly reduce a company's carbon emissions. The workshop highlighted that rebuild feasibility studies can help reduce the risk and test out more innovative rebuild designs with higher emission reduction potentials.

This was also discussed as an enabler because equipment that lasts longer justifies larger investments.

> A senior manager at a glass manufacturing company stated: *"There is a furnace repair, once every 15 years. You have the opportunity to make major changes. At this time, the plant looks at new furnace, machines, major repair of furnace, inspection technology. It is critical at that time: the planning of any environmental abatement equipment is done with the operational planning of the production facilities."*
>
> A senior manager at a glass manufacturing company stated: *"We have an investment cycle of 15-20 years. A decision we make now, we will have to live with for 20 years. We can't gamble, we could cause problems for our customers, and make a good plant uneconomically viable, and create job loss."*

The ninth barrier – **difficulty to find external financing** – was identified in the literature (Venmans, 2014 and Centre for Low-Carbon Future, 2011) and was confirmed by the interviews, surveys and workshop participants. The difficulty to find external financing, like grants or RD&D funds, limits the adoption of technologies with longer payback periods.

Lack of resources deployed to identifying the funding available, and reluctance to move to third party financing are seen as additional barriers to finding external financing as mentioned above. Workshop participants and interviewees also indicated that there is a lack of collaboration on financing demonstration projects as this is seen as a competitive advantage and thus sharing the financial burden amongst manufacturers is limited. There were discussions that companies could go through with a renewable energy investment if a third party invested in upfront costs to share the risk of a longer payback this supports the sixth enabler that third party investments can aid in the area of financing. Workshop participants stated that it is difficult to convince people to implement non-technical innovative procedures through alternative finance models, since it is more difficult to foresee benefits on paper. Participants indicated a general reluctance to go out of conventional capex method and that there is limited financial innovation. Engagement is needed to educate people to move away from conventional financing.

> A senior manager at a glass manufacturing company said: *"The application processes for grants are complex, and have many caveats."*

"Lack of financial support for R&D: Some respondents commented on the difficulty of accessing government support to promote industry R&D." (Centre for Low-carbon Futures 2011)

The tenth barrier – **risk of production disruption, hassle and inconvenience** – was identified in the literature (Ricardo AEA, 2013; JRC, 2013 and Venmans, 2014) and was confirmed during the interviews, surveys and workshop. Thus, retrofit capability is limited.

Risk of production disruptions from retrofit technologies is an even larger concern for small companies with limited production capacity. Management commitment is generally needed for any energy efficiency retrofit project as if anything goes wrong; it impacts on plant level employee performance KPIs. Interviewees were concerned about retrofits or installing new technologies and its implications on quality and being able to continue to meet customer demands.

A senior manager at a glass manufacturing company said: *"We can't gamble, we could cause problems for our customers, and make a good plant uneconomically viable, and create job loss."*

The eleventh barrier – **low demand risk** – was identified in the literature (Venmans, 2014) and was confirmed by surveys and workshop discussions. Efficiency investments entail fixed costs that may be cost-inefficient when there is over-capacity during economic downturns.

Companies may not be able to recover fixed investment costs if demand for glass products and therefore revenues decline. However, the interviewees indicated that the container glass sector for example was not hit that heavily by the recession, whereas flat glass was impacted more. Workshop participants indicated this risk effects regions differently and that it is difficult to identify a solution to overcome this barrier. Participants were of the opinion that this was down to the economy, variable costs, demand, and taking investment risks. Participants highlighted that low demand risk is linked with growing competition.

The key findings are summarised within section 3.1 of this report.

3.5 Technologies to Reduce Carbon Emissions

A view of major energy saving opportunities is shown in Figure 8.

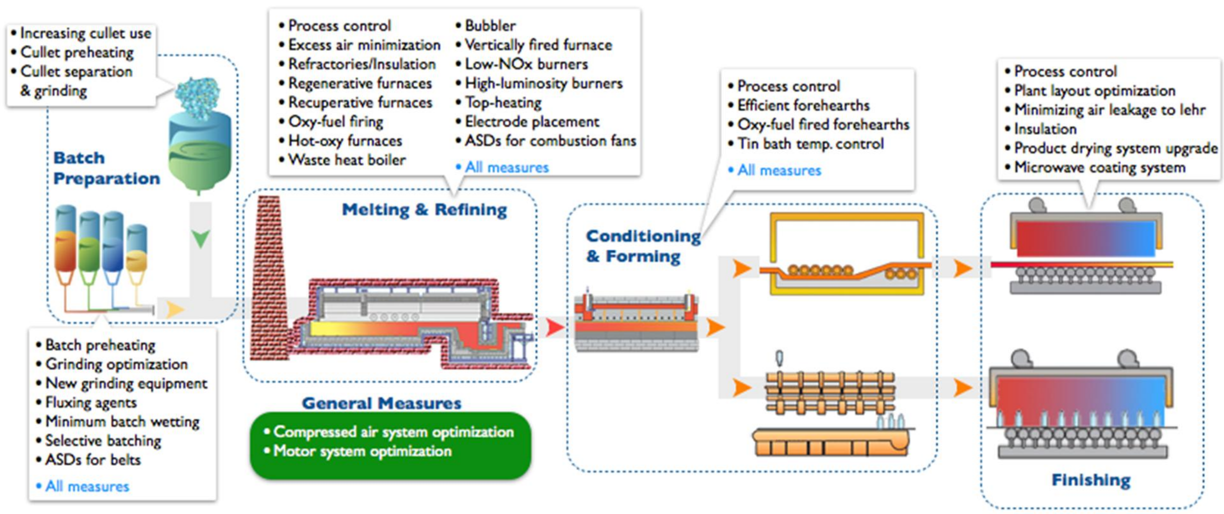

Figure 8: Energy saving opportunities in glass manufacturing (Institute for Industrial Productivity, 2014)

The options distilled from the literature review, interviews, evidence-gathering workshop, discussions with Trade Associations and input from academia are presented in appendix C (the data for these options are also listed). The energy-saving and decarbonisation opportunities are classified into eight categories that represent the principal areas of the glass making process and key cross-cutting areas of potential performance improvement, in order to group similar technology options:

- Raw Materials: batch pelletisation, batch reformulation, and increased use of recycled glass (cullet).
- Furnace: conventional improved furnace construction (end-fired furnace, regenerative furnace, recuperative furnace, increased furnace size, improved furnace insulation, sealed furnace), innovative improved furnace construction (sub-merged combustion melting, hot-oxy glass, LoNOx, Heye melter, Vortec pre-heater and pre-melter, plasma melting, segmented or tailored modular melting, high-speed convection, speed up melting process, and advanced glass melter), and oxy-fuel combustion.
- Improved Process Control: infrared analysis in forehearth, adaptive process controller (APC), continuous gob monitoring system (CGMS), and intelligent glass melting concept (IGMC).
- Waste Heat Recovery: electricity from waste heat, raw materials pre-heating, CHP, waste heat boiler, thermo-chemical recuperator (TCR), organic rankine cycle (ORC) system, and thermo-photovoltaic (TPV).
- Fuel Switching: fuel switch to electricity (electric melting and electrification or boosting), fuel switching to biogas (bio-SNG) or hydrogen, and renewables generation.
- Carbon Capture: carbon capture and storage (CCS), carbon capture and utilisation (CCU), and biological carbon capture (BCC).
- General Utilities: overall energy management, compressed air, electric motors and VSD/ASD, heat and steam distribution, and lighting.
- Product Design: light-weight containers, energy efficient flat glass, and light-weight flat glass.

This short list of options was used in the pathway analysis (section 4).

3.5.1 Biomass Carbon Intensity

Pathways including biomass reflect biomass carbon intensity (unless the biomass in the pathway is assumed to be waste biomass). The carbon intensities (below) are applied to two scenarios to help reflect and bound the uncertainties around biomass carbon availability: these are (i) unlimited availability (as deployed in the Max Tech pathway) or (ii) no availability.

In all cases, combustion emissions are assumed to be zero (in line with EU Renewable Energy Directive methodology), on the basis that all biomass used is from renewable sources and thus additional CO_2 is removed from the atmosphere equivalent to that emitted on combustion. This means that all biomass is assumed to be sourced from material that meets published sustainability criteria.

Given the wide variation in pre-combustion emissions, a carbon intensity (based on pre-combustion emissions) derived from a low scenario from the DECC-commissioned Bio-Energy Emissions and Counterfactual Model report (2014). An emission value of 20 kg CO_{2e}/MWh_{th} has been used for solid biomass use, and this has been modified to 25 kg CO_{2e}/MWh_{th} if the pathway includes pyrolysis, and 30 kg CO_{2e}/MWh_{th} if the pathway includes production of biogas.

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3.5.2 Costs of Options

Limited information related to the capital cost of technologies was identified in this project as summarised in appendix C. In gathering capital cost-related data, literature or engagement with stakeholders, together with expert judgement, were used to establish an initial order of magnitude dataset for use in the cost analysis assessment. The degree of stakeholder engagement in relation to the cost dataset was lower than for the carbon reduction pathways. Operating costs such as energy use changes, energy costs and labour are not included in this analysis, although we recognise that operating costs will have a major impact on the decarbonisation pathways. For example, some options (e.g. carbon capture and electrification of firing) will greatly increase energy use and costs of a process plant.

Costs analysis was carried out for the pathways, which is presented in section 4. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the research and development stage. As well as costs of operation and energy use, other significant costs not included in the analysis are research, development, demonstration, civil works, modifications to plant and costs to other stakeholders, which are significant for many options. Great care must be taken in how these costs are interpreted and it is recommended to check with trade associations.

4. PATHWAYS

4.1 Key Points

Two Max Tech pathways, one using carbon capture and storage or utilisation (CCS/U) as a disruptive technology, the other using electric melting in that role, produce a reduction in emissions of 83% compared with emissions in 2012. Significant reductions of 60% and 91% could be achieved under Challenging World and Collaborative Growth scenarios respectively. The majority of these reductions have been achieved through the deployment of CCS/U and oxy-fuel combustion technologies, or electric melting and the use of biogas. Feedback from the workshop showed that the glass sector strongly preferred electric melting technology to CCS/U as a potential decarbonisation solution.

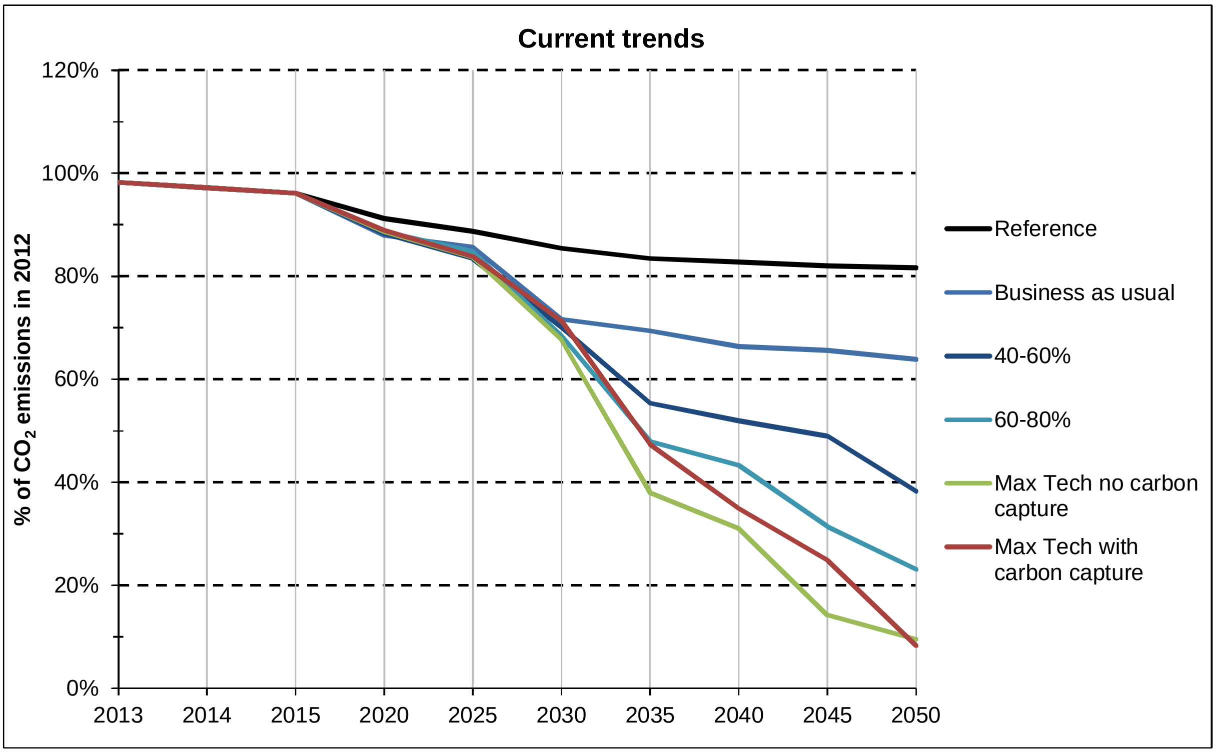

Figure 9: Performance of pathways for the current trends scenario

Figure 9 shows the wide range of decarbonisation and energy efficiency pathways that are possible for the current trends scenario.

- Business as Usual (BAU) represents a pathway where existing trends in energy efficiency and decarbonisation continue and current SAT technologies are deployed starting in 2015 with most of them deployed to 100% by 2030.
- 40-60% CO_2 reduction pathway includes maximal deployment of all State-of-the-Art equipment and additional deployment of batch reformulation and a limited amount of electric melting.
- 60-80% CO_2 reduction pathway builds further on the previous pathway and includes some more advanced (innovative) furnace design improvements.
- Max Tech pathway with electric melting includes all State-of-the-Art and more innovative technologies. In addition, the sector switches some of its fuel use to biogas and deploys more electric melting.

- Max Tech pathway with CCS/U includes all State-of-the-Art and Major Investment Technologies and deploys CCS/U to a technical maximum for the sector, and also some electric melting.

Only one option shown in the deployment tables – fuel switching to hydrogen - is not deployed in any pathway, based on evidence from interviews and workshops that hydrogen is a much less attractive decarbonised fuel gas than bio-methane. The combustion properties of hydrogen are considerably different to methane, and the quality of the flame is not conducive to furnace operation. It has been retained in the tables for completeness but shows zero deployment.

Pathway analysis was based on the 'maximum interaction' case, as this gave the minimal, worst-case CO_2 reductions. Maximum interaction means that where multiple options could apply to the same emissions, emissions are assumed to be saved only once, i.e. by one of the options only, to avoid potential double-counting.

It should be noted that the modelling does not take into account any potential changes in emissions due to factory extensions. Emissions could increase by installing additional equipment to create value-added products or to obtain additional pollution abatement. Also, some options, such as oxy-fuel and CCS/U, would require more electricity to operate and would actually produce more CO_2 emissions at current grid carbon intensity. These options cannot therefore contribute to decarbonisation unless the grid is sufficiently decarbonised by 2050.

4.2 Pathways and Scenarios – Introduction and Guide

The pathways development uses evidence gathered, as set out in section 3, to create a set of decarbonisation and energy efficiency pathways, which provide a quantitative component to the roadmap and help inform the strategic conclusions.

A pathway consists of decarbonisation options deployed over time from 2015 to 2050, as well as a reference emissions trend. The analysis covers three: 'scenarios': with pathways developed under a central trend ('current trends' scenario) and alternative future outlooks ('challenging world' and 'collaborative growth' scenarios).

A scenario is a specific set of conditions that could directly or indirectly affect the ability of the sector to decarbonise. Examples of these are: future decarbonisation of the grid, future growth of the sector, future energy costs, and future cost of carbon. Since we do not know what the future will look like, using scenarios is a way to test the robustness of the different pathways. A detailed description of these scenarios is provided in appendix A.

The three scenarios were developed, covering a range of parameters. They characterise possible versions of the future by describing assumptions relating to international consensus; international economic context; resource availability and prices; international agreements on climate change; general technical innovation; attitude of end consumers to sustainability and energy efficiency; collaboration between sectors and organisations; and demographics (world outlook). These scenarios were used during the workshop to help decide on deployment rate for the different options.

Quantitative parameters were also part of the scenarios, including production outlook (agreed sector-specific view) and grid CO_2 factors (DECC supplied) which both impact decarbonisation (assuming production and carbon emissions have a linear directly proportional relationship). Other quantitative parameters within the scenarios governed forward price forecasts and technology deployment.

The purpose of the model that underpins this pathways analysis is to bring together the data captured from various sources and to broadly reflect, using a simple "top down" approach, how emissions might develop to

2050. The model is therefore capable of indicating magnitudes of emission savings that can be achieved, when various technology options are applied, and also how different deployment timings and high-level economic outlooks for a sector might change the results. A sector model was used to create pathways based on reference emissions and energy consumption in 2012. The model is not intended to give exact results and is not of sufficient detail to account for all mass/ energy/ carbon flows, losses and interactions in a sector (i.e. it is not "bottom up" and does not use automatic optimisation techniques).

The methodology is summarised in Figure 10.

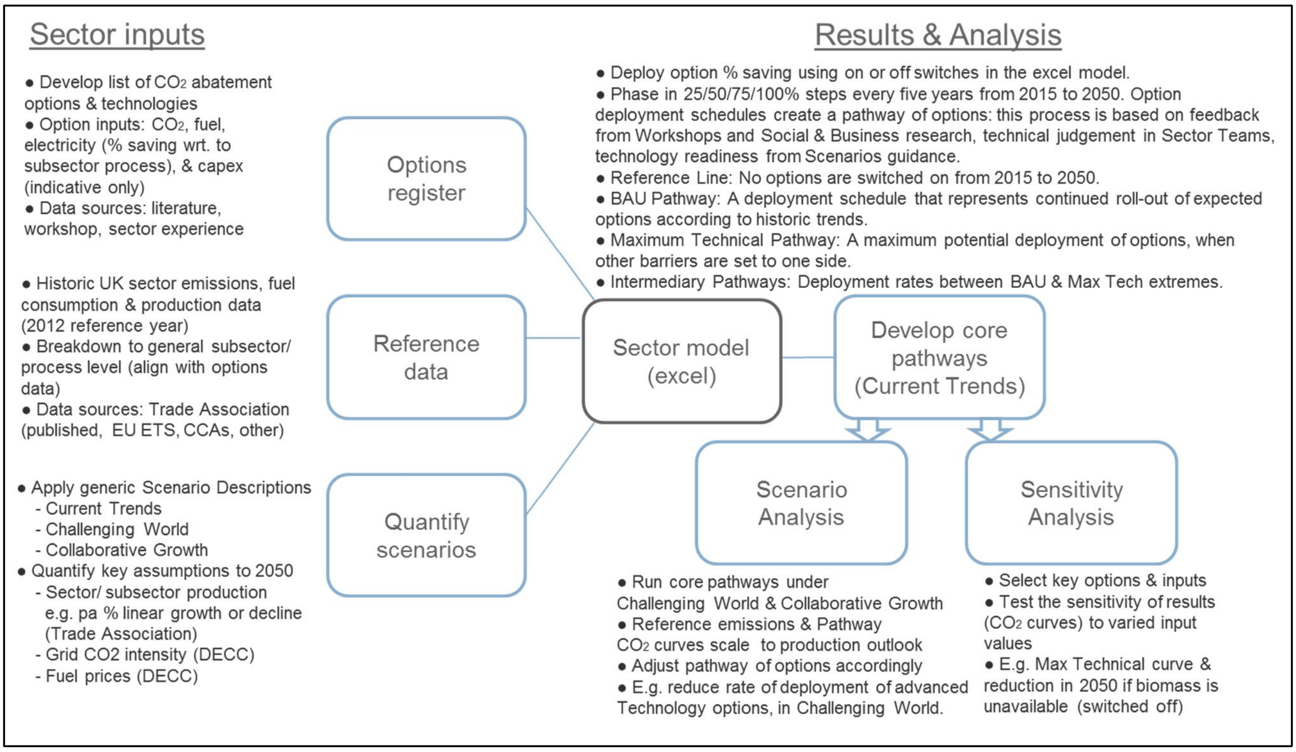

Figure 10: Summary of analysis methodology

This section of the report is structured to present the pathways in the current trends scenario (section 4.4), whilst also briefly describing how the pathways change when modelled under other scenarios. Table 13 illustrates this structure and acts as a guide to the section. Appendix D summarises the pathway analysis in the other two scenarios (challenging world and collaborative growth).

Pathway	Current Trends Scenario	Challenging World Scenario	Collaborative Growth Scenario
Reference Emissions Trend	Scenario assumptions only linked to production outlook and grid decarbonisation. No options are deployed in the model.		
BAU	Builds on the reference line by deploying options from 2015 to 2050 in the model, to construct a BAU pathway. Run model under current trends.	Builds on BAU pathway current trends by adjusting option selections and deployment schedule, to reflect the scenario assumptions and technology constraints. Run model under challenging world.	Adjust BAU pathway current trends, i.e. option selections and deployment schedule, to reflect scenario assumptions and technology constraints. Run model under collaborative growth.
20-40%[13]	Builds on BAU for example by: deploying more advanced options, extending further across sector, deploying options earlier. Run under current trends.	Builds on 20-40% CO_2 reduction pathway current trends in the same way. Run under challenging world.	Adjust 20-40% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
40-60%	Builds on 20-40% in the same way. Run under current trends.	Builds on 20-40% CO_2 reduction pathway current trends in the same way. Run under challenging world.	Adjust 20-40% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
60-80%	Builds on 40-60% in the same way. Run model under current trends.	Builds on 40-60% CO_2 reduction pathway current trends in the same way. Run under challenging world	Adjust 40-60% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
Max Technical	Configure a schedule of options from 2015 to 2050 that broadly represents a maximum rate and spread across the sector. Run model under current trends.	Adjust Max Tech pathway current trends in the same way. Run under challenging world.	Adjust Max Tech pathway current trends in the same way. Run under collaborative growth.

Table 13: Pathways and scenario matrix

Section 4.5 presents results from the sensitivity analysis, which aims to demonstrate the impact of key options and sensitivity of the pathways to critical inputs. Section 4.6 presents the analysis of pathway costs. Section 4.7 summarises the barriers and enablers to the options and pathways developed in the modelling, taking account of information gathered from literature and stakeholders.

4.3 Baseline evolution - Principal Question 3

This section provides assessment of the range of questions under principal question 3: ‘How might the baseline level of energy and emissions in the sectors change over the period to 2050?’

[13] Intermediary pathways may or may not be developed for a sector, depending on the carbon reductions of the BAU and Max Tech pathways.

The container glass manufacturing industry produces a range of glass containers and other products. The industry's performance depends on downstream demand for container glass, which primarily comes from food and beverage producers. Manufacturers are competing with substitute products like plastic packing materials. A meagre annual growth is expected through 2020 (IBIS World, 2014).

The flat glass industry is expected to return to consistent growth through 2020. In the last five years, the subsector has not done particularly well, mainly due to the recession and subsequent fall off in demand from the automotive and construction sectors, which are key downstream industries for flat glass (IBIS World, 2013). It is expected that the subsector will grow rapidly in the short term, as the UK recovers from recession. After that growth, the industry will likely stay constant.

Under the Challenging World scenario, container production is estimated to decrease slightly and for flat glass production a higher decline is projected. Under the Collaborative World scenario, however, production is assumed to grow. It is anticipated that customers will desire more light-weight glass products, but at the same time will demand more luxury products (like champagne or whisky which are often sold in heavy bottles).

Based on the above assumptions and together with British Glass, we have developed the following growth estimates for the different future scenarios:

- Current trends – 0% annual growth for container glass, 3.7% annual growth for flat glass until 2019 then 0% annual growth.
- Challenging world – 0.5% annual decline for container glass, 1% annual decline for flat glass.
- Collaborative growth – 1% annual growth for container glass, 3.7% annual growth for flat glass until 2019 then 1% annual growth.

4.4 Emission-Reduction Potential and Pathway Analysis – Principal Question 4 and 5

This section provides an assessment of the range of questions under principal questions 4 and 5:

- What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050?
- What emissions pathways might each sector follow over the period to 2050, under different scenarios?

For a detailed description of the pathways development and analysis methodology, please see appendix A.

The list of barriers and enablers has informed the list of technical options that are being deployed in the different pathways. They also informed the deployment of the different technical options both with regards to time and degree of deployment. For example the enabler 'strong recycling culture', led to an increase in the deployment of higher rates of recycled glass.

In addition to the growth or decline projections for the different scenarios, the following electricity grid emission factors were used in the modelling:

- Current trends: 100g CO_2 per kWh by 2030 and 26g CO_2 per kWh in 2050.
- Challenging world: 200g CO_2 per kWh by 2030 and 150g CO_2 per kWh by 2050.
- Collaborative growth: 50g CO_2 per kWh by 2030 and 25g CO_2 per kWh by 2050.

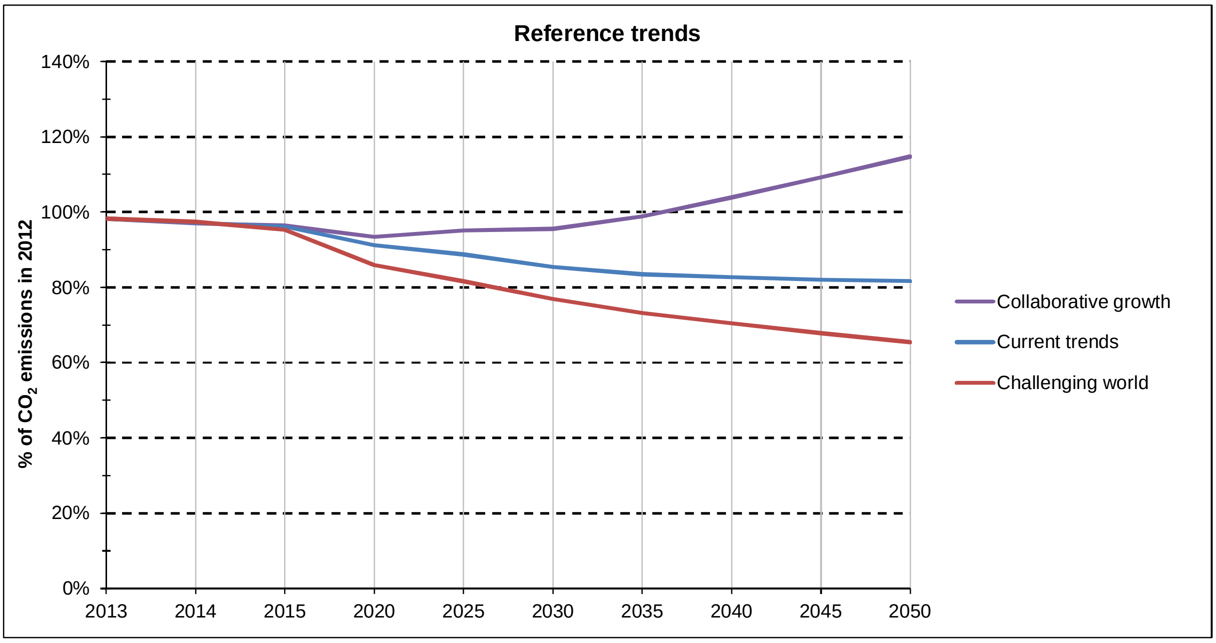

Figure 11: Reference trends for the different scenarios

For all of the pathways, to have the total CO_2 reduction, growth or decline of the sector, indirect (emissions from using electricity from the electricity grid) and direct emissions need to be accounted for. The indirect emissions and growth or decline of the sector are illustrated by the reference trend. In Figure 11 the reference trends for the different scenarios are shown. The shape of the trend is linked both to growth or decline of the sector and the different levels of decarbonisation of the electricity grid.

4.4.1 Baseline - Business as Usual Pathway

Pathway Summary

The guiding principle for the BAU pathway was to outline a set of decarbonisation and energy savings options that would be expected if current rates of efficiency improvement in the UK glass industry continued, and no significant intervention or outside support was provided to decarbonise the sector by 2050. Options requiring no policy intervention (compared to today) and only minor changes within the sector were therefore chosen. It should be noted that the BAU pathway still requires significant investments by the glass sector, for example to improve furnace efficiencies.

Deployment for the Current Trends scenario

Figure 12 shows the option deployment for the BAU pathway under the current trends scenario. This figure shows the different technical options on the left, followed by estimated adoption rate (ADOP.) in 2012, followed by the applicability rate (APP.). This applicability rate indicates to what level this option is applicable to the sector. To the right of the applicability rate is the modelled deployment of the option over time to 2050. The CO_2 reduction is calculated by the model based on the adoption rate, applicability rate and deployment. All option deployments consider the output of the social and business research, in terms of the impact on the timing and levels of deployment of each option, as well as current investment cycles. The applicability rate has been assumed to be 100% for all options, because it is assumed that it will be possible to overcome all barriers to implementation. Factors such as availability of space on site have not been taken into account. Further studies would be required to determine feasibility.

In the BAU pathway under current trends, incremental and current State-of-the-Art (SAT) technologies were initially the only technologies deployed, starting in 2020-2030 at a low rate, with other technologies being deployed later in the period where there was a perceived business case to implement these, most of them deployed to 25% or less by 2050. This deployment was confirmed during the second workshop and by British Glass members. In practice, the deployment in a glass plant would be linked to its investment cycle.

Pathway: Business As Usual Scenario: Current Trends (CT)

OPTION	ADOP.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
01 BATCH PELLETISATION	0%	100%	0%	0%	0%	0%	0%	0%	25%	25%	25%
02 BATCH REFORMULATION	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
03 CARBON CAPTURE	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 ELECTRIC MELTING	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 WASTE HEAT RECOVERY - ELECTRICITY FROM WASTE HEAT	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%
06 FUEL SWITCHING - GAS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 FUEL SWITCHING - HYDROGEN	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 GENERAL UTILITIES {From 2012 level}	0%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
09 IMPROVED FURNACE CONSTRUCTION - CONVENTIONAL {From 2012 level}	0%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
10 IMPROVED FURNACE DESIGN - INNOVATIVE	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11 IMPROVED PROCESS CONTROL {From 2012 level}	0%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
12 INCREASED USE OF Recycled glass - Container	56%	100%	0%	0%	0%	0%	25%	25%	25%	25%	25%
13 INCREASED USE OF Recycled Glass - Flat	28%	100%	0%	0%	0%	0%	25%	25%	25%	25%	25%
14 OXY-FUEL COMBUSTION	0%	100%	0%	0%	0%	0%	10%	10%	10%	10%	10%
15 WASTE HEAT RECOVERY- RAW MATERIALS PRE-HEATING	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%
16 RENEWABLE GENERATION	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%
17 WASTE HEAT RECOVERY - other	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%

Figure 12: Option deployment for the BAU pathway

In this pathway, the principal options that contribute to the emissions reduction in 2050 are (Figure 13):

- **Increased use of recycled glass**, deployed to 25% of the full capability from 2030 onwards, accounting for 35% of the total emissions reduction from deployment of options in 2050. The deployment of this option depends on an increased availability of suitable cullet.
- **Conventional improvements to furnace construction**, deployed gradually from 2020 to reach full deployment in 2050, accounting for 22% of the total emissions reduction from deployment of options in 2050.
- **Waste heat recovery** (the combined effect of raw materials pre-heating and other waste heat recovery options), deployed to 5% of potential in 2020 and increased to 10% from 2030, accounting for 13% of the total emissions reduction from deployment of options in 2050.
- **Improved process control**, deployed gradually from 2020 to reach full deployment in 2050, accounting for 10% of the total emissions reduction from deployment of options in 2050.
- **Oxy-fuel combustion**, deployed to 5% of potential in 2020 and increased to 10% from 2030, accounting for 7% of the total emissions reduction from deployment of options in 2050. and
- **Batch pelletisation**, deployed to 25% of potential starting from 2040, accounting for 5% of the total emissions reduction from deployment of options in 2050.

Notably, the general utilities option that reduces electricity consumption is deployed gradually from 25% in 2020 to full potential in 2050, but this option does not contribute greatly to the total emissions reduction as a result of the ongoing electricity grid decarbonisation.

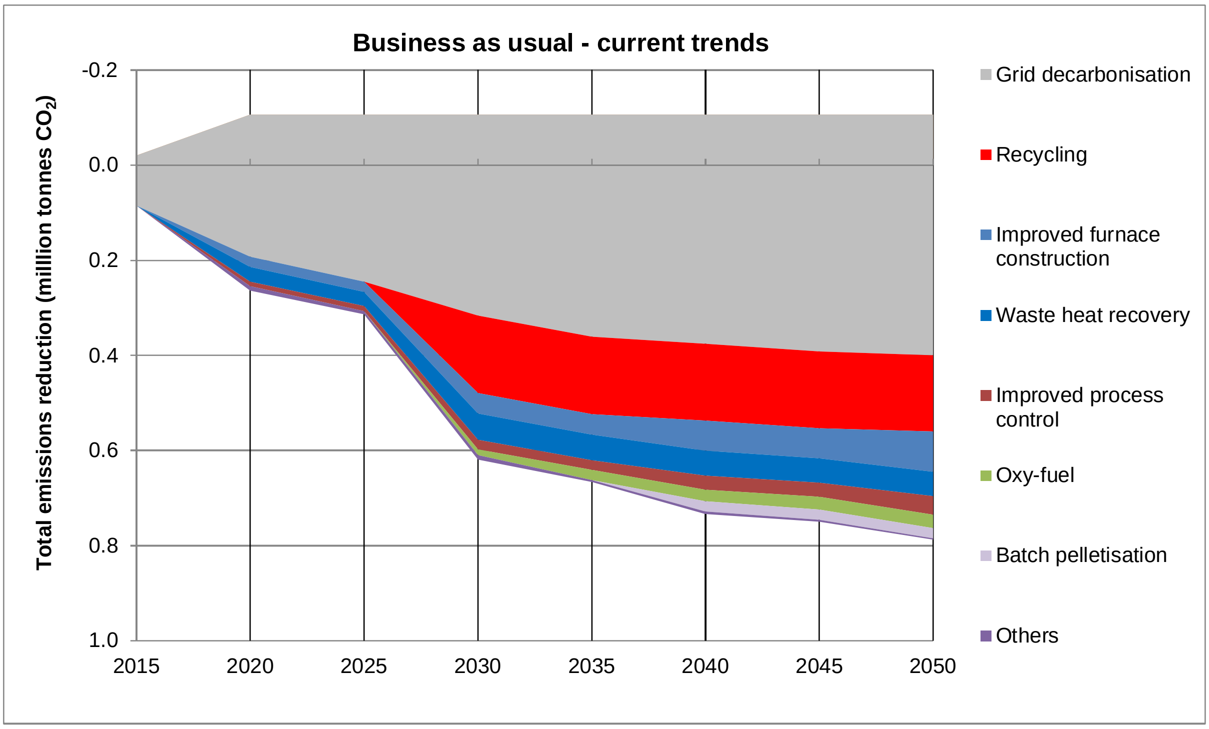

Figure 13: Contribution of principal options to the absolute emissions reduction throughout study period, for the BAU pathway, current trends scenario

For the current trends scenario, this pathway gives an overall reduction of 36% in 2050, compared to 2012. This includes the emission reductions linked to the deployment of options and decarbonisation of the grid as well as the emission increase linked to the growth of the sector.

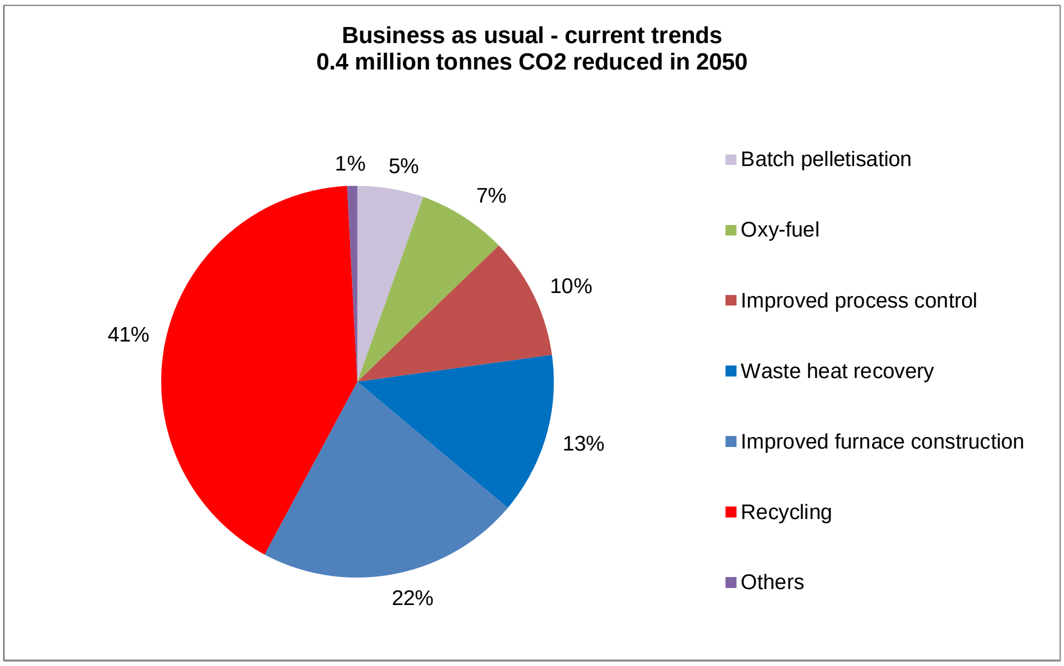

Figure 14: Breakdown of 2050 emissions reduction, for the BAU pathway, current trends scenario

The CO_2 reduction contribution in 2050 revealed that the biggest carbon reduction in BAU came from a few key options (Figure 14): recycling; improved furnace construction; waste heat recovery; and improved process control.

Option Deployment for other Scenarios

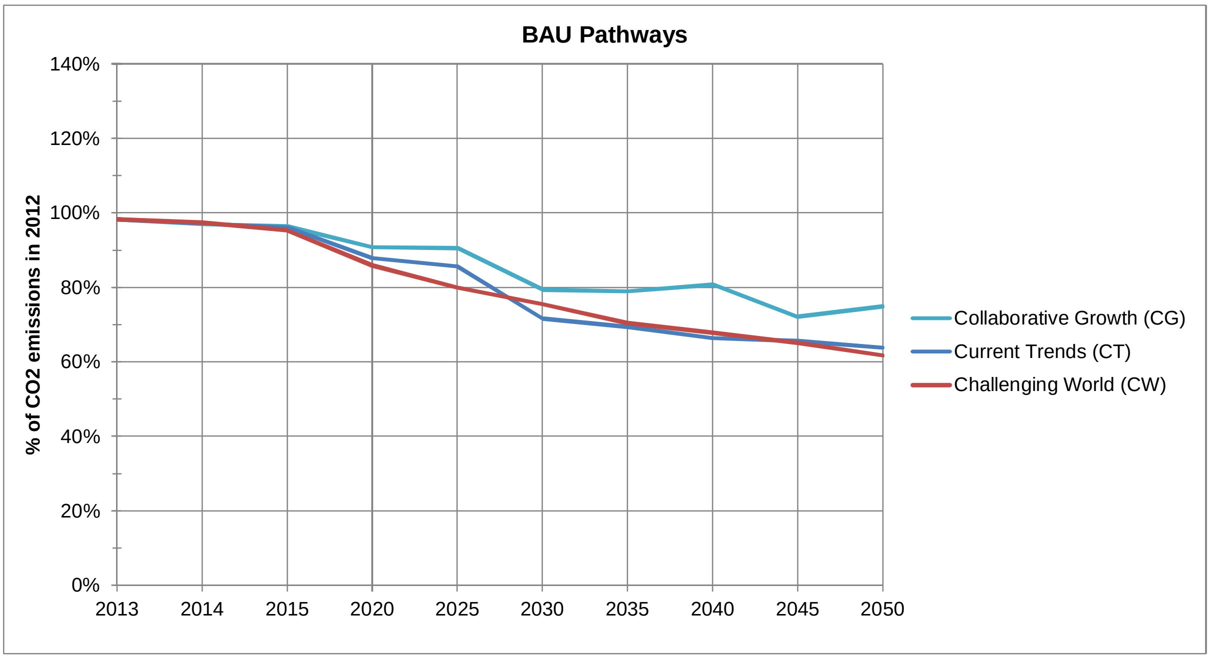

Figure 15: BAU pathways for the different scenarios

Figure 15 shows the BAU pathways for the different scenarios. As can be seen, the current trend scenario delivers an overall CO_2 reduction of 36%, the Challenging World scenario delivers an overall CO_2 reduction of 38% and the Collaborative Growth scenario delivers an overall reduction in CO_2 of 25%.

In the challenging world scenario, due to the more challenging business and investment climate, the following options are no longer deployed in the BAU pathway: increased recycling of glass, waste heat recovery, and batch pelletisation. Improvements to general utilities, conventional furnace construction and process control are deployed at a slower rate and no longer reach full deployment by 2050.

In the collaborative growth scenario, most of the technologies are expected to be deployed more quickly than under current trends and reach higher deployment levels by 2050. Electricity prices will rise, increasing the incentives to generate electricity on-site. Glass recycling will be improved, resulting in increased use of cullet. Conventional furnace improvements will occur marginally earlier, but reduce in 2050 as some conventional furnaces are replaced by innovative furnace designs, which are deployed in 2050.

Detailed information on the modelled deployment of options for the challenging world and collaborative growth scenario is shown in appendix D.

4.4.2 20-40% CO_2 Reduction Pathway

Pathway Summary

As the BAU pathway achieves a CO_2 reduction of over 20% in the current trends and challenging world scenario, it is not necessary to develop a 20%-40% CO_2 reduction pathway for this scenario. Under Challenging World, the BAU pathway reaches almost 60% CO_2 reduction, again making a 20%-40% CO_2

reduction pathway for this scenario obsolete. Therefore, only for the collaborative growth scenario, a 20%-40% CO_2 reduction pathway was developed. Under this scenario, production was assumed to grow. BAU options – like glass recycling, waste heat recovery, conventional and innovative furnace construction, oxy-fuel combustion and batch pelletisation – were deployed at an increasing rate, and electric melting was introduced with a deployment of 25% in 2050 and batch reformulation to 25%. The CO_2 reduction for this pathway was 28% in 2050 compared to 2012.

The deployment of options for the collaborative growth scenarios for this pathway is shown in appendix D.

4.4.3 40-60% CO_2 Reduction Pathway

Pathway Summary

The 40-60% CO_2 reduction pathway was reached by maintaining certain options like oxy-fuel combustion and waste heat recovery from the current trends BAU pathway. Other options are deployed marginally earlier (general utilities and improved process control) or at a faster rate (waste heat recovery - electricity from waste heat and increased use of cullet) or both earlier and at a faster rate (batch pelletisation). Some additional options, selected on their technical applicability, ease of adoption and economic considerations, are deployed: batch reformulation and electric melting. Conventional furnace improvements no longer reach 100% deployment by 2050, but stall at 75%, since the remainder of the conventional furnaces have been replaced with new electric melt furnaces.

Deployment for the Current Trends scenario

Figure 16 shows the option deployment for the 40-60% CO_2 reduction pathway for the current trends scenario.

Pathway: 40% - 60%   Scenario: Current Trends (CT)

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 BATCH PELLETISATION	0%	100%	0%	0%	0%	25%	25%	25%	50%	50%	75%
02 BATCH REFORMULATION	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	50%
03 CARBON CAPTURE	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 ELECTRIC MELTING	0%	100%	0%	0%	0%	0%	10%	25%	25%	25%	25%
05 WASTE HEAT RECOVERY - ELECTRICITY FROM WASTE HEAT	0%	100%	0%	0%	10%	10%	10%	25%	25%	25%	50%
06 FUEL SWITCHING - GAS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 FUEL SWITCHING - HYDROGEN	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 GENERAL UTILITIES {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
09 IMPROVED FURNACE CONSTRUCTION - CONVENTIONAL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	75%	75%
10 IMPROVED FURNACE DESIGN - INNOVATIVE	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11 IMPROVED PROCESS CONTROL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
12 INCREASED USE OF Recycled glass - Container	56%	100%	0%	0%	0%	0%	25%	25%	25%	25%	50%
13 INCREASED USE OF Recycled Glass - Flat	28%	100%	0%	0%	0%	0%	25%	25%	25%	25%	50%
14 OXY-FUEL COMBUSTION	0%	100%	0%	0%	0%	0%	10%	10%	10%	10%	10%
15 WASTE HEAT RECOVERY- RAW MATERIALS PRE-HEATING	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	40%
16 RENEWABLE GENERATION	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%
17 WASTE HEAT RECOVERY - other	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%

Figure 16: Option deployment for the 40-60% CO_2 reduction pathway

In this pathway, the principal options that contribute to the emissions reduction in 2050 are (Figure 17):

- **Electric melting**, deployed to 10% of potential in 2030 and 25% from 2035 onwards, accounting for 33% of the total emissions reduction from deployment of options in 2050.
- **Increased use of recycled glass**, deployed to 25% of the full capability from 2030 and increased to 50% in 2050, accounting for 30% of the total emissions reduction from deployment of options in 2050.

- **Waste heat recovery** (the combined effect of raw materials pre-heating and other waste heat recovery options), deployed to 25% in 2035 and increased to 40% in 2050 (raw materials pre-heating), and to 5% in 2020 and increased to 10% in 2030 (other), accounting for 13% of the total emissions reduction from deployment of options in 2050.
- **Batch pelletisation**, deployed to 25% of potential starting from 2025 and reaching 75% deployment in 2050, accounting for 6% of the total emissions reduction from deployment of options in 2050.
- **Conventional improvements to furnace construction**, deployed gradually from 2020 to reach 75% deployment in 2050, accounting for 6% of the total emissions reduction from deployment of options in 2050.
- **Batch reformulation,** deployed to 25% in 2035 and 50% in 2050, accounting for 4% of the total emissions reduction from deployment of options in 2050.
- **Improved process control**, deployed gradually from 2020 to reach full deployment in 2050, accounting for 4% of the total emissions reduction from deployment of options in 2050.

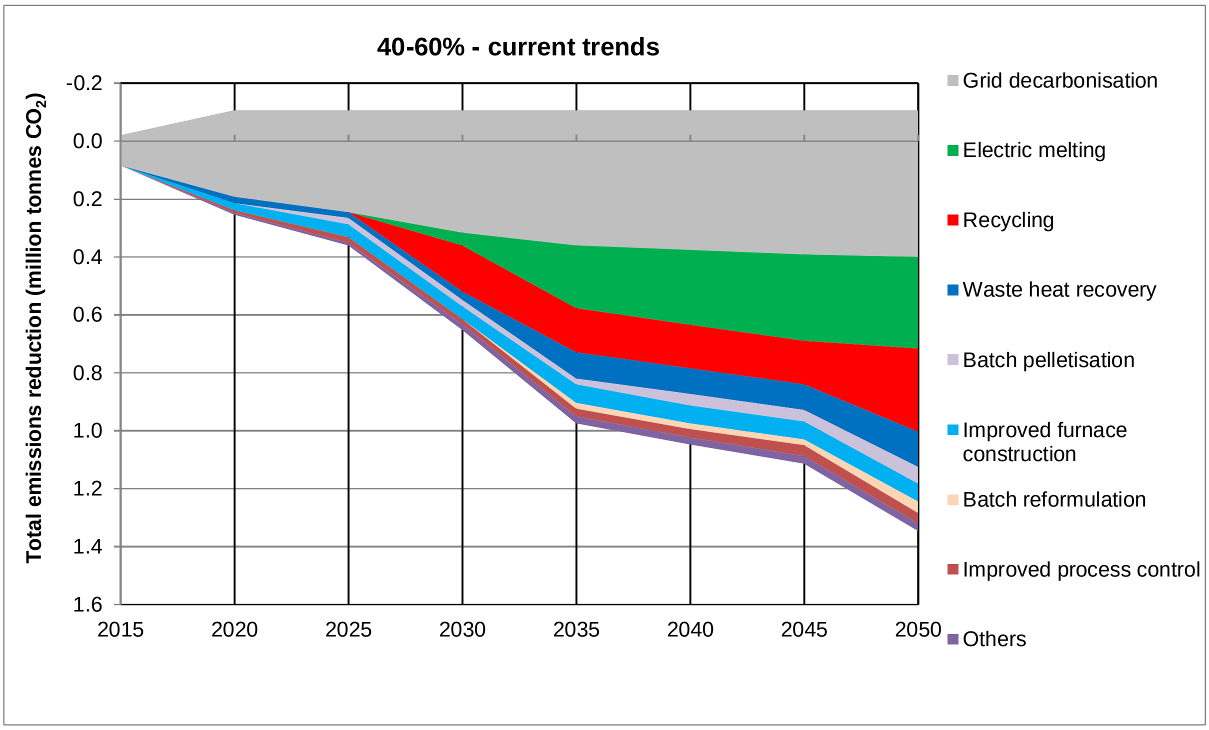

Figure 17: Contribution of principal options to the absolute emissions reduction throughout study period, for the 40-60% CO_2 reduction pathway, current trends scenario

For the current trends scenario, this pathway gives an overall reduction of 62% in 2050, compared to 2012. This includes the emission reductions linked to the deployment of options and decarbonisation of the grid as well as the emission increase linked to the growth of the sector.

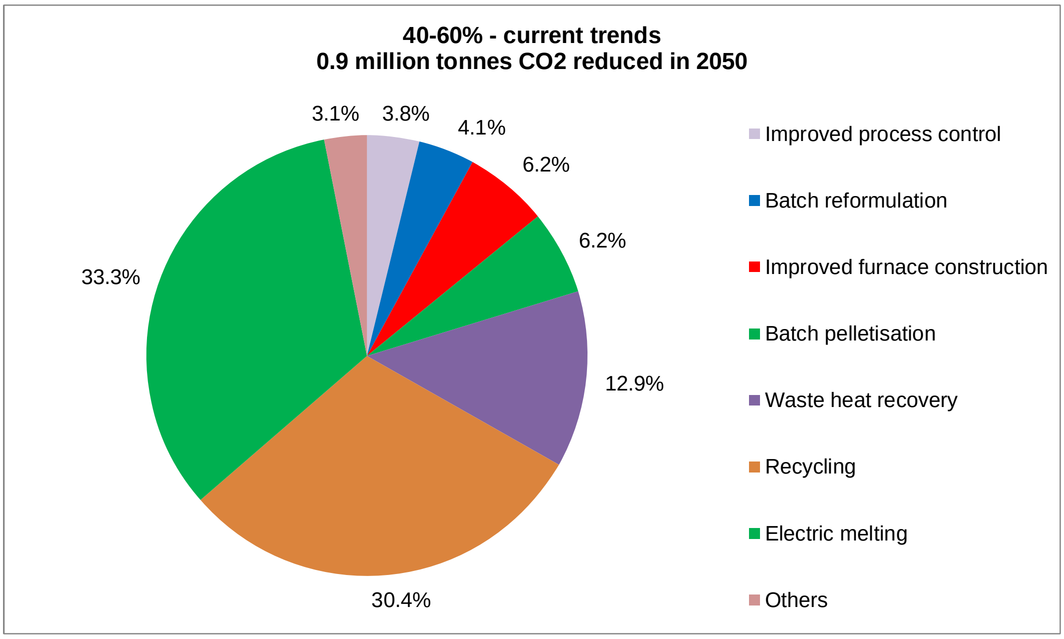

Figure 18: Breakdown of 2050 emissions reduction, for the 40-60% CO_2 reduction pathway, current trends scenario

The CO_2 reduction contribution in 2050 revealed that the biggest carbon reduction in this pathway came from a small number of key options (Figure 18): electric melting; recycling; and waste heat recovery.

Option Deployment for other Scenarios

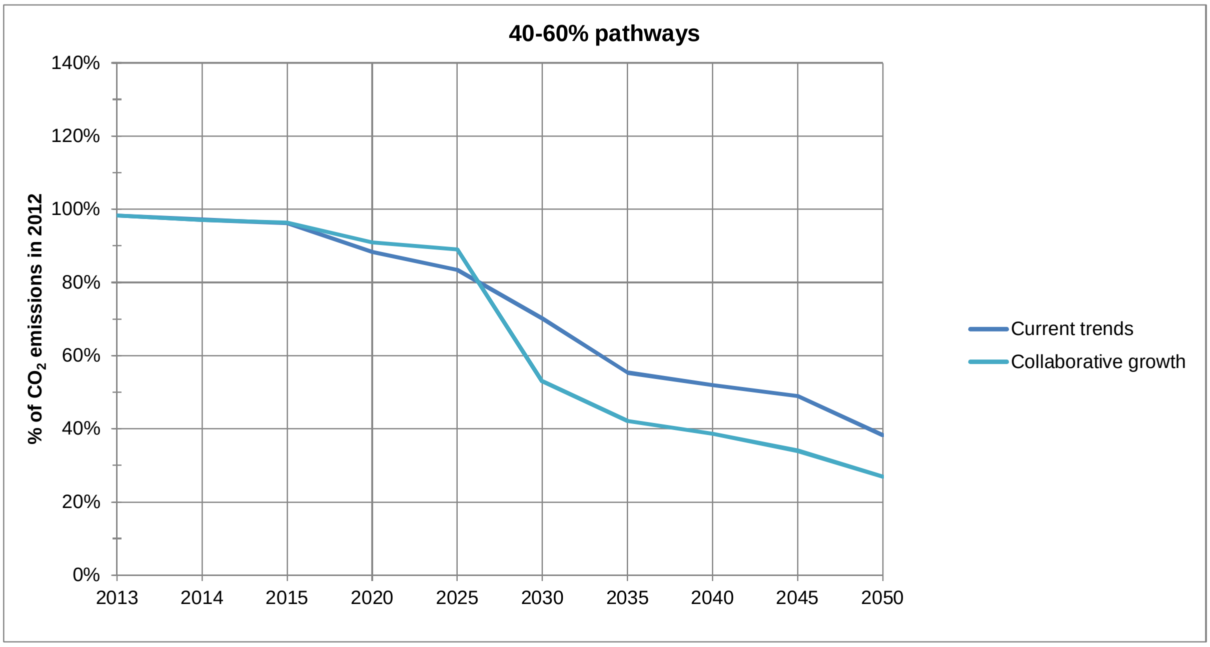

Figure 19: 40-60% CO_2 reduction pathways for the different scenarios

Figure 19 shows the 40-60% CO_2 reduction pathways for the current trends and collaborative world scenarios. As can be seen, the current trend scenario delivers an overall CO_2 reduction of 62% and the collaborative growth scenario delivers an overall reduction in CO_2 of 73%. The BAU pathway achieves over 40% reduction for the challenging world scenario so no additional 40-60% CO_2 reduction pathway was developed for that scenario.

In the collaborative growth scenario, batch pelletisation and raw material pre-heating are deployed at a slower rate, with a focus more on advanced technology options such as electric melting. Conventional furnace improvements decline, because some innovative furnace design comes into place by 2050. Cullet use increases for container glass but remains the same for flat glass. Other options deployments are comparable with the current trends scenario.

The deployment of options for the collaborative growth scenario for this pathway is shown in appendix D.

4.4.4 60-80% CO_2 Reduction Pathway

Pathway Summary

The 60-80% CO_2 reduction pathway under the current trends scenarios includes the same options deployments as the 40-60% CO_2 reduction pathway under current trends, and adds the deployment of innovative furnace design starting from 2045 and reaching 25% by 2050. Deployment of increased cullet use is increased to 60% for container glass but remains the same for flat glass.

Deployment for the Current Trends Scenario

Figure 20 shows the option deployment for the 60-80% CO_2 reduction pathway for the current trends scenario.

Pathway: 60% - 80%   Scenario: Current Trends (CT)

OPTION	ADOP.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
01 BATCH PELLETISATION	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	50%
02 BATCH REFORMULATION	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	50%
03 CARBON CAPTURE	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 ELECTRIC MELTING	0%	100%	0%	0%	0%	0%	25%	50%	50%	50%	50%
05 WASTE HEAT RECOVERY - ELECTRICITY FROM WASTE HEAT	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	25%
06 FUEL SWITCHING - GAS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 FUEL SWITCHING - HYDROGEN	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 GENERAL UTILITIES {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
09 IMPROVED FURNACE CONSTRUCTION - CONVENTIONAL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	75%	75%
10 IMPROVED FURNACE DESIGN - INNOVATIVE	0%	100%	0%	0%	0%	0%	0%	0%	0%	25%	25%
11 IMPROVED PROCESS CONTROL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
12 INCREASED USE OF Recycled glass - Container	56%	100%	0%	0%	0%	0%	25%	25%	25%	50%	60%
13 INCREASED USE OF Recycled Glass - Flat	28%	100%	0%	0%	0%	0%	25%	25%	25%	25%	50%
14 OXY-FUEL COMBUSTION	0%	100%	0%	0%	0%	0%	10%	10%	10%	10%	10%
15 WASTE HEAT RECOVERY- RAW MATERIALS PRE-HEATING	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	15%
16 RENEWABLE GENERATION	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%
17 WASTE HEAT RECOVERY - other	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%

Figure 20: Option deployment for the 60-80% reduction pathway

In this pathway, the principal options that contribute to the emissions reduction in 2050 are (Figure 21):

- **Electric melting**, deployed to 25% of potential in 2025 and 50% from 2035 onwards, accounting for 48% of the total emissions reduction from deployment of options in 2050.
- **Increased use of recycled glass**, deployed to 25% of the full capability from 2030 and rising to 60% and 50% in 2050 for container and flat glass respectively, accounting for 24% of the total emissions reduction from deployment of options in 2050.
- **Innovative furnace design**, deployed to 25% of potential from 2045, accounting for 8% of the total emissions reduction from deployment of options in 2050.

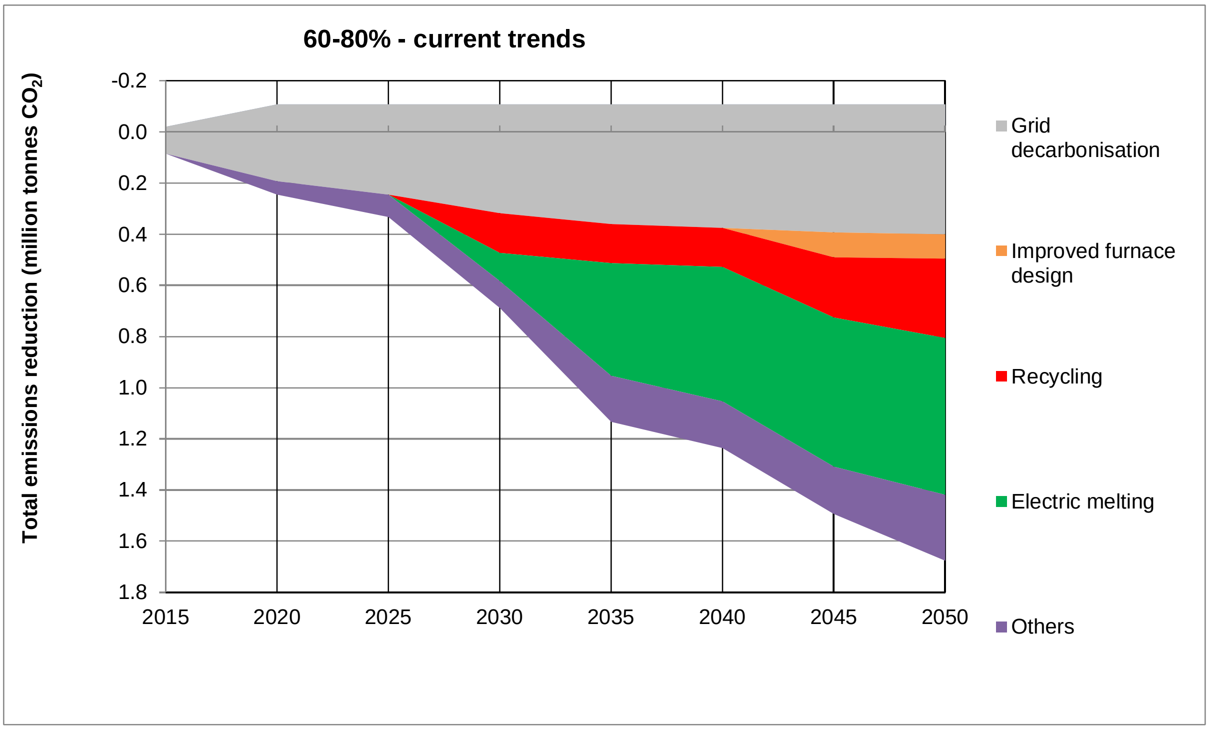

Figure 21: Contribution of principal options to the absolute reduction throughout the study period, for the 60-80% reduction pathway, current trends scenario

For the current trends scenario, this pathway gives an overall reduction of approximately 77% in 2050, compared to 2012. This includes the emission reductions linked to the deployment of options and decarbonisation of the grid as well as the emission increase linked to the growth of the sector.

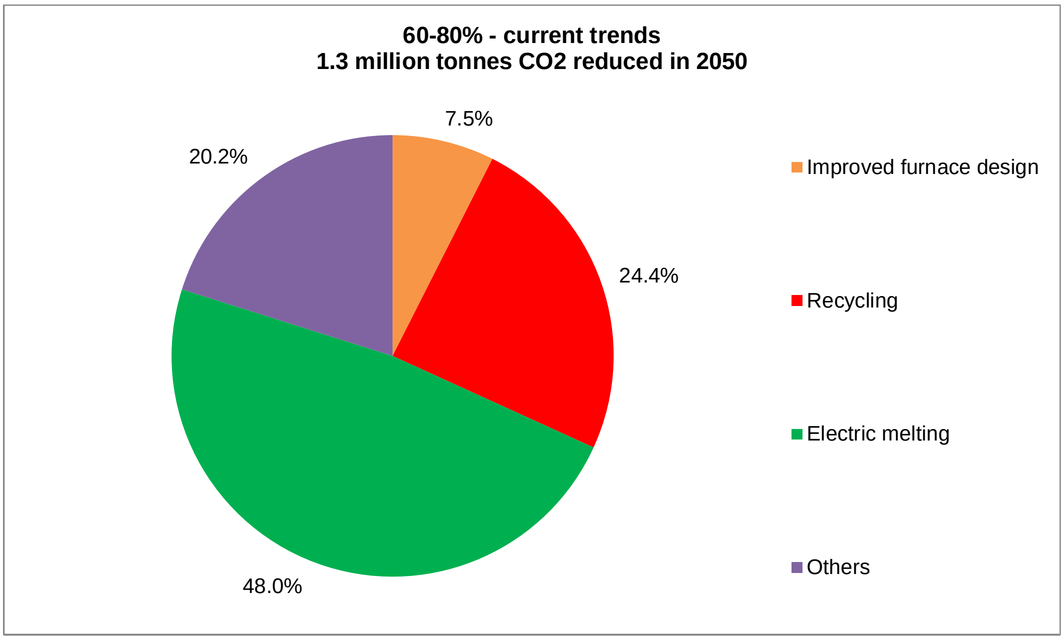

Figure 22: Breakdown of 2050 emissions reduction, for the 60-80% reduction pathway, current trends scenario

The CO_2 reduction contributions in 2050 revealed that the biggest carbon reduction in this pathway come from a small number of key options (Figure 22): electric melting, recycling, and improved furnace design.

Option Deployment for other Scenarios

No 60-80% CO_2 reduction pathways were developed for the two other scenarios.

4.4.5 Maximum Technical Pathway without CCS

Pathway Summary

The first Max Tech pathway is based on electric melting, fuel switching and increased use of recycled glass, and does not include CCS/U. Under the current trends scenario, a lot of the same options are deployed as in the 60-80% CO_2 reduction pathway. Raw materials preheating, however, is deployed at a higher rate by 2050, together with batch pelletisation and electric melting. Waste heat is no longer available, hence electricity from waste heat can no longer be used. For container glass, cullet use increases some more up to 70% by 2050. Conventional furnace improvements are deployed at a lower rate up to 50% by 2040 and then even decline to 15% by 2050, because innovative furnace design is slowly introduced. The option of fuel switching to biogas is for the first time introduced in this pathway, as it is now required to reach the required level of decarbonisation.

Deployment for the Current Trends Scenario

Figure 23 shows the option deployment for the Max Tech pathway without CCS/U for the current trends scenario.

Pathway: Max Tech no CCS Scenario: Current Trends (CT)

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 BATCH PELLETISATION	0%	100%	0%	0%	0%	25%	25%	25%	50%	50%	75%
02 BATCH REFORMULATION	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	50%
03 CARBON CAPTURE	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 ELECTRIC MELTING	0%	100%	0%	0%	0%	0%	25%	50%	50%	60%	60%
05 WASTE HEAT RECOVERY - ELECTRICITY FROM WASTE HEAT	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
06 FUEL SWITCHING - GAS	0%	100%	0%	0%	0%	0%	0%	25%	30%	40%	40%
07 FUEL SWITCHING - HYDROGEN	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 GENERAL UTILITIES {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
09 IMPROVED FURNACE CONSTRUCTION - CONVENTIONAL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	50%	50%	15%	15%
10 IMPROVED FURNACE DESIGN - INNOVATIVE	0%	100%	0%	0%	0%	0%	0%	0%	0%	25%	25%
11 IMPROVED PROCESS CONTROL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
12 INCREASED USE OF Recycled glass - Container	56%	100%	0%	0%	0%	0%	25%	25%	25%	50%	70%
13 INCREASED USE OF Recycled Glass - Flat	28%	100%	0%	0%	0%	0%	25%	25%	25%	25%	50%
14 OXY-FUEL COMBUSTION	0%	100%	0%	0%	0%	0%	10%	10%	10%	10%	10%
15 WASTE HEAT RECOVERY- RAW MATERIALS PRE-HEATING	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	25%
16 RENEWABLE GENERATION	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%
17 WASTE HEAT RECOVERY - other	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%

Figure 23: Option deployment for the Max Tech pathway without CCS/U

In this pathway, the principal options that contribute to the emissions reduction in 2050 are (Figure 24):

- **Electric melting**, deployed to 25% of potential in 2025 and reaching 60% in 2050, accounting for 37% of the total emissions reduction from deployment of options in 2050.
- **Fuel switching to biogas**, deployed to 25% in 2035 and reaching 40% in 2045, accounting for 27% of the total emissions reduction from deployment of options in 2050.
- **Increased use of recycled glass**, deployed to 25% of the full capability from 2030 and rising to 70% and 50% in 2050 for container and flat glass respectively, accounting for 18% of the total emissions reduction from deployment of options in 2050.

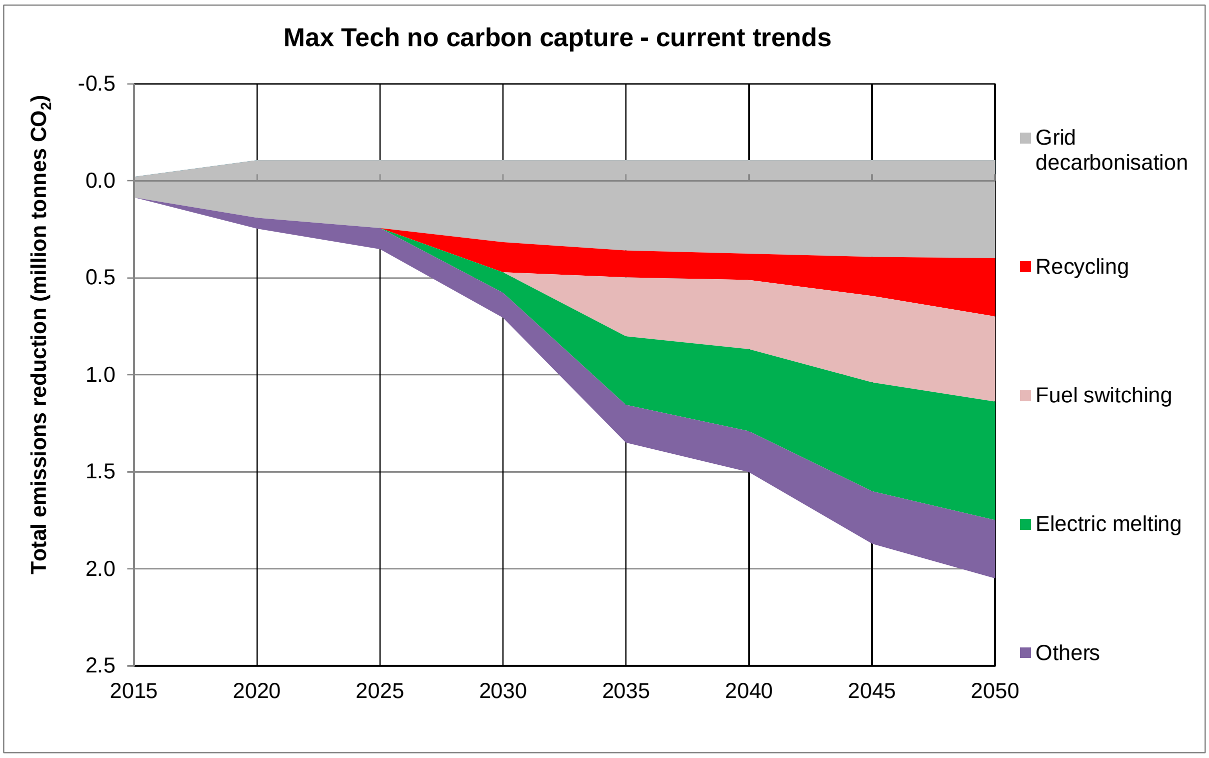

Figure 24: Contribution of principal options to the absolute throughout the study period, for the Max Tech 1 pathway, current trends scenario

For the current trends scenario, the options deployed in this pathway give an overall reduction of approximately 90% in 2050, compared to 2012. This includes the emission reductions linked to the deployment of options and decarbonisation of the grid as well as the emission increase linked to the growth of the sector.

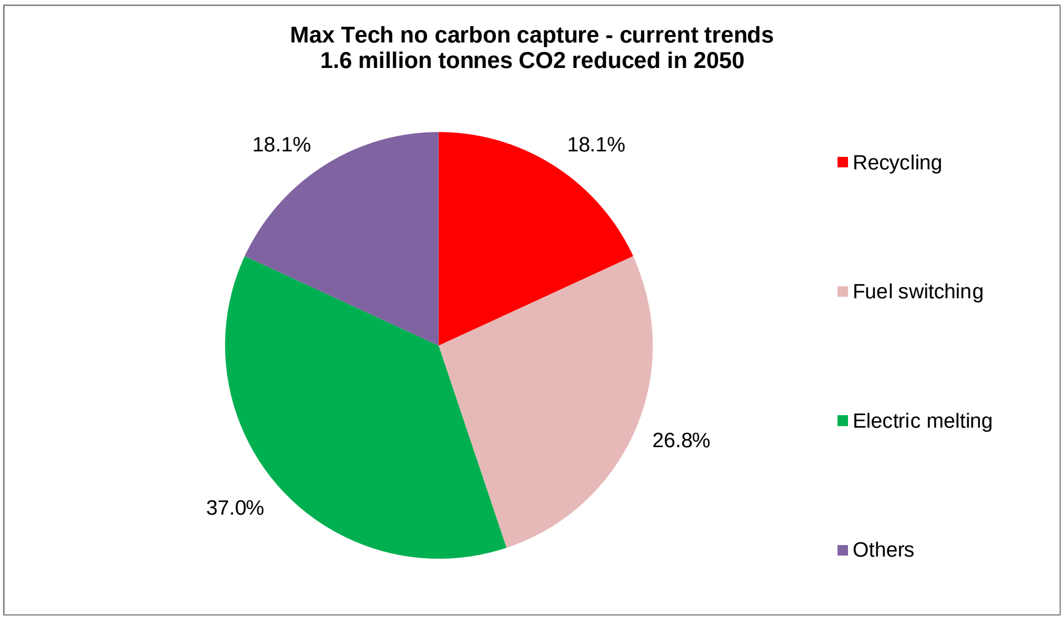

Figure 25: Breakdown of 2050 emissions reduction, for the Max Tech pathway without CCS/U, current trends scenario

The CO_2 reduction contribution in 2050 revealed that the biggest carbon reduction in this pathway came from a small number of key options (Figure 25): electric melting, fuel switching to biogas, and recycling.

Option Deployment for other Scenarios

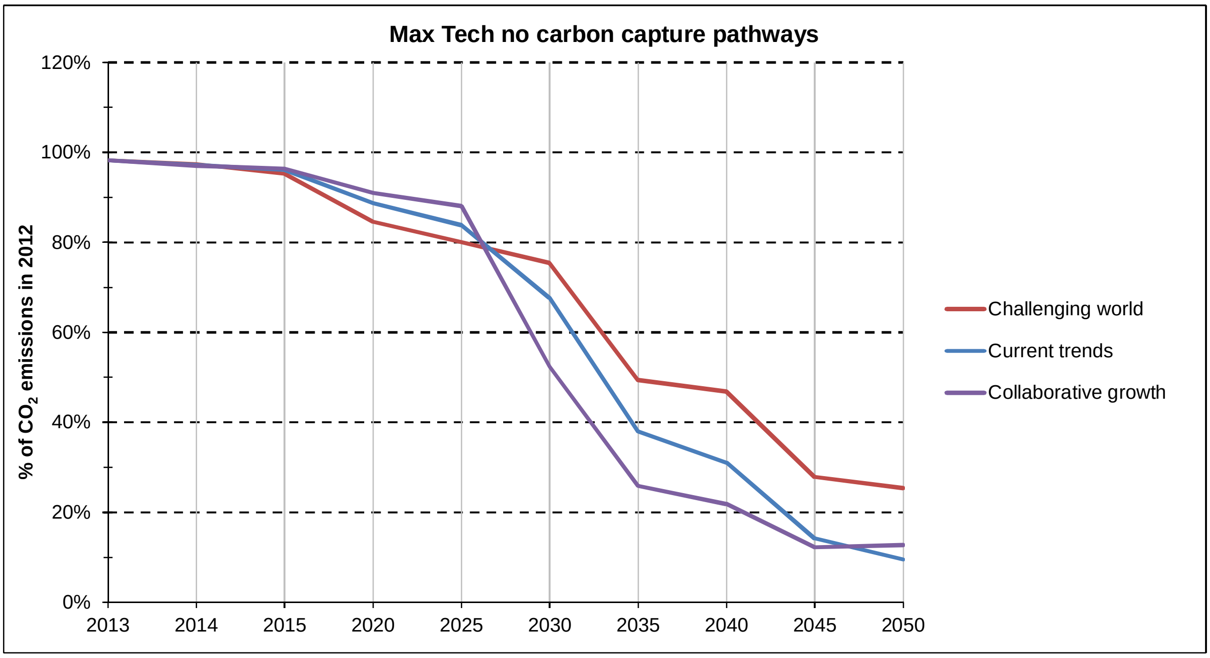

Figure 26: Max tech pathways without CCS/U for the different scenarios

Figure 26 shows the Max Tech pathways without CCS/U for the different scenarios. As can be seen, the current trends scenario delivers a CO_2 reduction of 90%, the challenging world scenario delivers a CO_2 reduction of 75% and the collaborative growth scenario delivers CO_2 reduction of 87%.

Under challenging world, option deployments are comparable to those under current trends, but generally happen later and to a lesser extent. However, electric melting and oxy-combustion are not deployed, since the level of grid decarbonisation under this scenario is insufficient to result in a net emissions reduction from their deployment. Some increase in fuel switching to biogas is therefore assumed to compensate for the loss of the electric melting option.

Under Collaborative Growth, electric melting happens earlier but to a lesser extent, whereas fuel switching to biogas is deployed at a higher rate. These changes are a reflection of the higher electricity prices anticipated under this scenario. Increased use of cullet is deployed at a higher rate. Conventional furnace design reaches 50% deployment by 2035 and then declines to 0% by 2050, because innovative furnace design is deployed at a higher rate.

The deployment of options for the challenging world and collaborative growth scenarios for this pathway is shown in appendix D.

4.4.6 Maximum Technical Pathway with CCS/U

Pathway Summary

Under current trends, the Max Tech pathway with CCS/U uses a combination of CCS/U and electric melting to reach the maximum decarbonisation level. The glass sector only has relatively small volumes of CO_2 available in comparison with other sectors. Moreover, extra abatement for gas cleaning would be required and extra electricity would be needed. However, CCS/U is still technically possible, and hence CO_2 capture could not be ignored when developing decarbonisation and energy efficiency pathways. Therefore, an extra Max Tech pathway was developed to include CCS/U and determine the added decarbonisation potential of this option.

CCS/U is deployed starting from 2035 to reach 75% deployment by 2050, and the other 25% of glass manufacturing sites implement electric melting. No fuel switching to biogas is deployed since it is not required when furnaces employ CO_2 capture, more innovative furnace designs are implemented, cullet use for container glass decreases and oxy-fuel combustion increases (as it goes hand in hand with CO_2 capture by making it cheaper). It should be noted that the use of oxy-fuel combustion facilitates the application of carbon capture, and it was therefore assumed that carbon capture would be employed on all of the sites that employed oxy-fuel combustion. But besides these changes, the Max Tech pathway with CCS/U is very comparable with the Max Tech pathway without CCS/U.

Deployment under Current Trends

Figure 27 shows the option deployment for the Max Tech pathway with CCS/CCU for the current trends scenario.

Pathway: Max Tech with CCS   Scenario: Current Trends (CT)

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 BATCH PELLETISATION	0%	100%	0%	0%	0%	25%	25%	25%	50%	50%	75%
02 BATCH REFORMULATION	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	50%
03 CARBON CAPTURE	0%	100%	0%	0%	0%	0%	0%	25%	50%	50%	75%
04 ELECTRIC MELTING	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	25%
05 WASTE HEAT RECOVERY - ELECTRICITY FROM WASTE HEAT	0%	100%	0%	0%	0%	0%	0%	13%	13%	13%	13%
06 FUEL SWITCHING - GAS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 FUEL SWITCHING - HYDROGEN	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 GENERAL UTILITIES {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
09 IMPROVED FURNACE CONSTRUCTION - CONVENTIONAL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	50%	25%
10 IMPROVED FURNACE DESIGN - INNOVATIVE	0%	100%	0%	0%	0%	0%	0%	0%	0%	25%	50%
11 IMPROVED PROCESS CONTROL {From 2012 level}	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
12 INCREASED USE OF Recycled glass - Container	56%	100%	0%	0%	0%	0%	25%	25%	25%	50%	70%
13 INCREASED USE OF Recycled Glass - Flat	28%	100%	0%	0%	0%	0%	25%	25%	25%	25%	50%
14 OXY-FUEL COMBUSTION	0%	100%	0%	0%	0%	0%	25%	25%	25%	50%	50%
15 WASTE HEAT RECOVERY- RAW MATERIALS PRE-HEATING	0%	100%	0%	0%	0%	0%	0%	13%	13%	13%	13%
16 RENEWABLE GENERATION	0%	100%	0%	0%	0%	0%	0%	10%	10%	10%	10%
17 WASTE HEAT RECOVERY - other	0%	100%	0%	0%	5%	5%	10%	10%	10%	10%	10%

Figure 27: Option deployment for the Max Tech pathway with CCS/U/CCU

In this pathway, the principal options that contribute to the emissions reduction in 2050 are (Figure 28):

- **Carbon capture**, deployed to 25% of potential in 2035 and reaching 75% in 2050, accounting for 39% of the total emissions reduction from deployment of options in 2050.
- **Increased use of recycled glass**, deployed to 25% of the full capability from 2030 and rising to 70% and 50% in 2050 for container and flat glass respectively, accounting for 18% of the total emissions reduction from deployment of options in 2050.
- **Electric melting**, deployed to 25% of potential from 2035 onwards, accounting for 15% of the total emissions reduction from deployment of options in 2050.
- **Innovative furnace design**, deployed to 25% of potential from 2045 and reaching 50% in 2050, accounting for 10% of the total emissions reduction from deployment of options in 2050.
- **Oxy-fuel combustion**, deployed to 10% in 2020 and reaching 50% in 2050, accounting for 6% of the total emissions reduction from deployment of options in 2050.

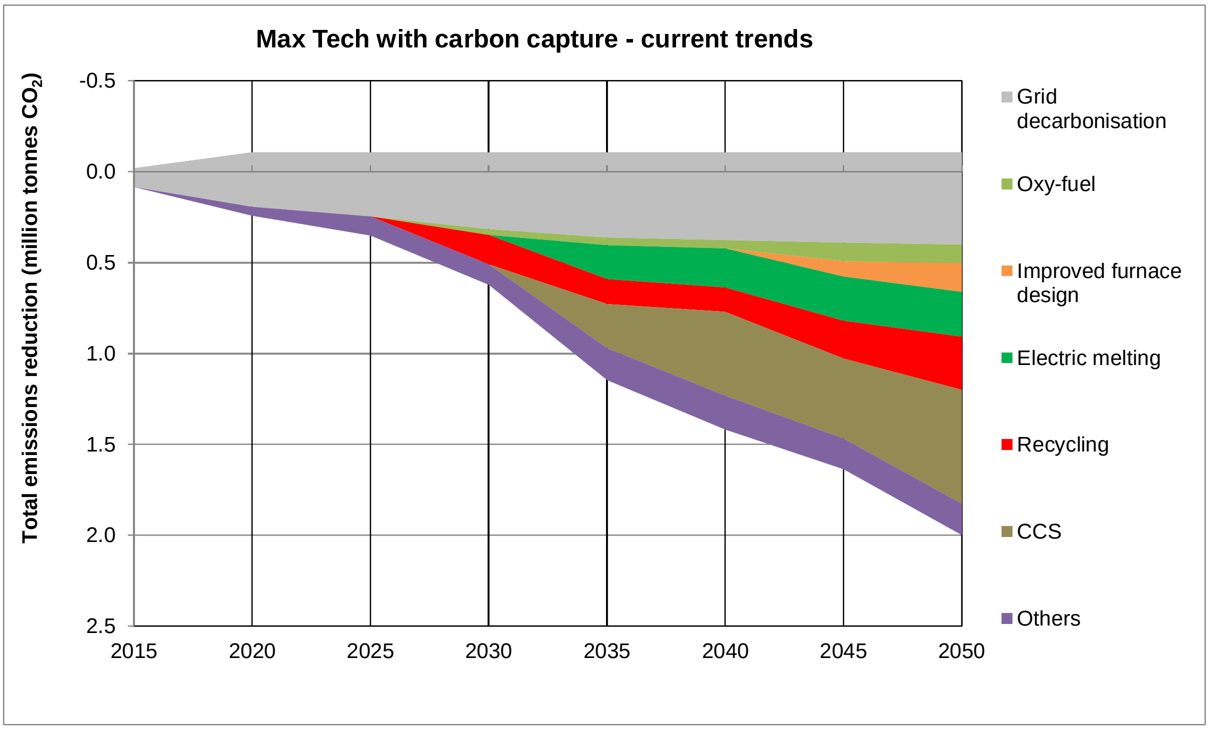

Figure 28: Contribution of principal options to the absolute emissions reduction throughout the study period, for the Max Tech 2 pathway, current trends scenario

For the current trends scenario, the options deployed in this pathway give an overall reduction of approximately 92% in 2050, compared to 2012. This includes the emission reductions linked to the deployment of options and decarbonisation of the grid as well as the emission increase linked to the growth of the sector.

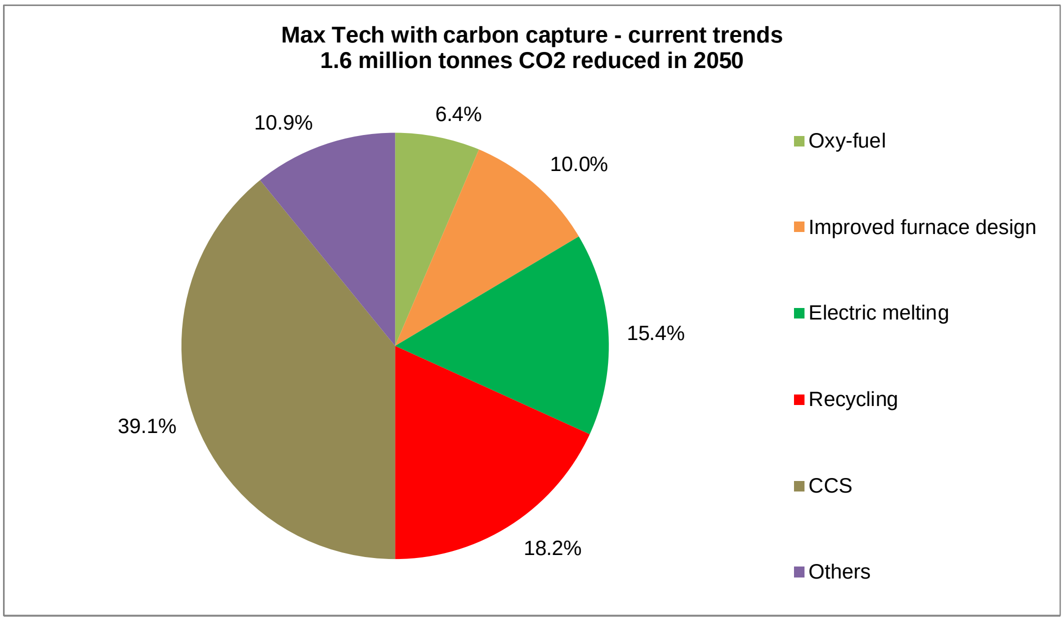

Figure 29: Breakdown of 2050 emissions reduction, for the Max Tech 2 pathway, current trends scenario

The CO_2 reduction contribution in 2050 revealed that the biggest carbon reduction in this pathway come from a small number of key options (Figure 29): CCS/U, recycling, and electric melting.

Option Deployment under Other Scenarios

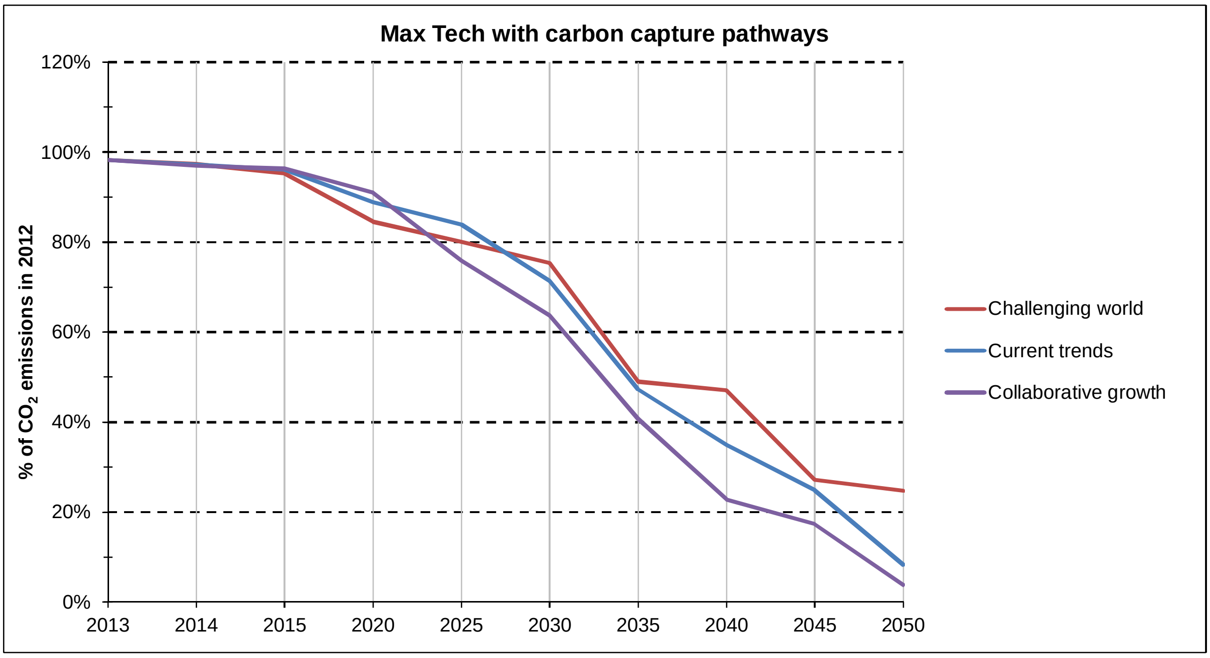

Figure 30: Max Tech pathway with CCS/U for the different scenarios

Figure 30 shows the Max Tech pathway with CCS/U for the different scenarios. As can be seen the current trend scenario delivers a CO_2 reduction of 92%, the challenging world scenario delivers a CO_2 reduction of 75% and the collaborative growth scenario delivers CO_2 reduction of 96%.

Under Challenging World, option deployments are comparable to those under current trends, but generally happen later and to a lesser extent. Only 25% deployment of CO_2 capture by 2050 is assumed (compared to 75% under current trends), which is therefore counteracted by a higher deployment percentage of conventional furnace improvements by 2050. However, electric melting and oxy-combustion are not deployed, since the level of grid decarbonisation under this scenario is insufficient to result in a net emissions reduction from their deployment. Deployment of fuel switching to biogas is therefore assumed to compensate for the loss of the electric melting option.

In the collaborative growth scenario, CO_2 capture is deployed earlier since the technology becomes commercially available earlier, and reaches 100% deployment by 2050; hence no electric melting is being deployed. No electric melting results in a higher deployment rate of cullet, and more CO_2 capture also means more oxy-fuel combustion. Also, to reach the absolute maximum in decarbonisation, renewable generation is deployed at 50% by 2050.

The deployment of options for the challenging world and collaborative growth scenarios for this pathway is shown in appendix D.

4.5 Sensitivity Analysis

Two sensitivities cases were run in the model to test the significance of key options on pathway outcomes and to highlight their importance in defining potential actions. Both of them were run on the Max Tech (no CCS) pathway in the current trends scenario to explore their impact on the base case.

Firstly, the Max Tech (no CCS) pathway was re-run without the 'fuel switching – gas' option being deployed in order to represent a case in which biomass fuel is not available. This option was replaced by increased deployment of the 'electric melting' option, with a limit imposed of 25% increments in deployment every 5 years. The sensitivity case pathway delivered lower CO_2 emissions reductions in 2035, 2045 and 2050 than the Max Tech (no CCS) pathway. There was a lowering of the emissions reductions in 2050 from 90% of 2012 emissions under the Max Tech (no CCS) pathway to an 85% reduction under the sensitivity case pathway.

Secondly, the Max Tech (no CCS) pathway was re-run without the 'electric melting' option being deployed in order to represent a case in which electrically heated furnace technology is not available for implementation or electricity is too expensive to make it commercially viable. This option was replaced by increased deployment of biomass fuel from the 'fuel switching – gas' option, with a limit imposed of 25% increments in deployment every 5 years. The sensitivity case pathway delivered greater CO_2 emissions reductions than the Max Tech (no CCS) pathway from 2030 onwards. There was an increase in the emissions reduction in 2050 from 90% of 2012 emissions under the Max Tech (no CCS) pathway to around 99% reduction under the sensitivity case pathway.

The main conclusion of the sensitivity analysis is that, in terms of emissions reduction, the use of biomass fuel is preferable to electric melting due to the indirect emissions from grid electricity used for electric melting being greater than the CO_2 emissions associated with the assumed carbon intensity of the biomass. This finding lends significance to the potential actions necessary to overcome the barriers to implementing the use of biomass within the sector.

The results of the two sensitivities for the Max Tech (no CCS) pathway are shown in Figure 31 below.

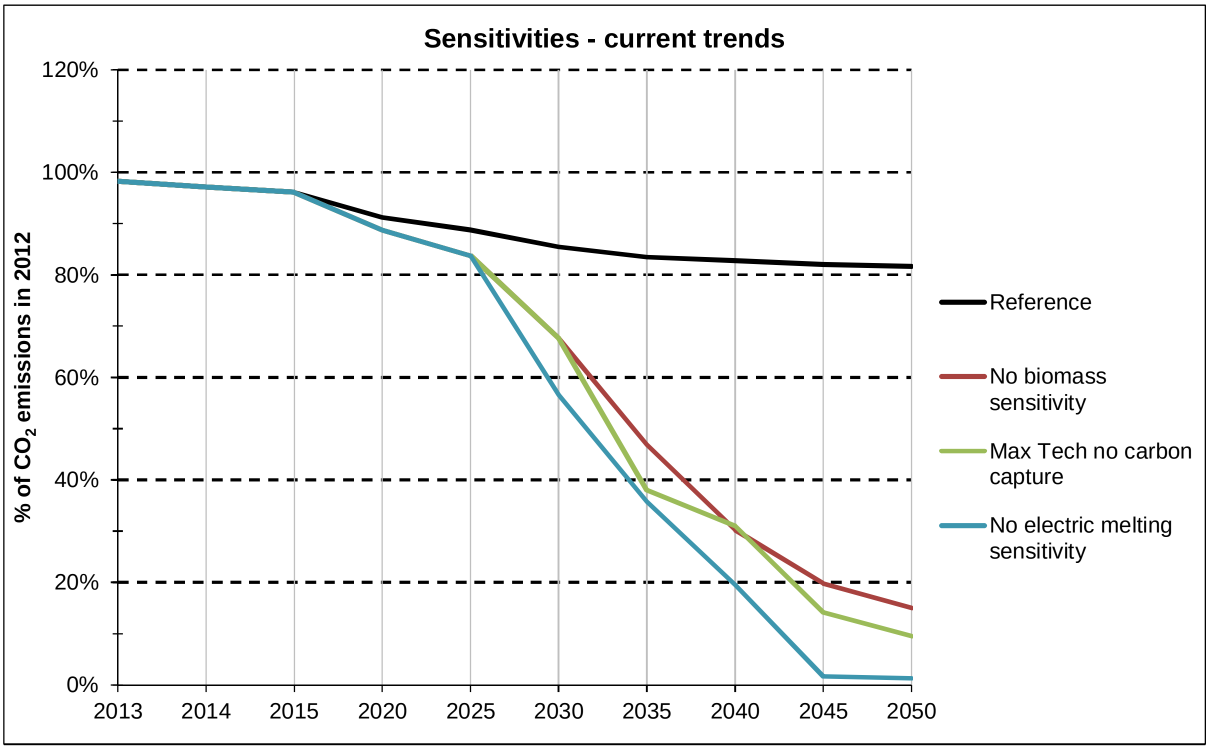

Figure 31: Pathways for current trends sensitivity analysis

In the option interaction calculation, the 'no interaction' case adds approximately 5% to the carbon reduction in 2050 in the Max Tech pathway.

4.6 Pathway Costs

4.6.1 Introduction

Estimates of the costs of new technologies or capital improvements with a time horizon to 2050 is fraught with difficulties. Any long term forecasts should be treated with caution. The cost analysis presented in this report is intended to provide a high level estimate of the total capital cost of each pathway to the UK as a whole, in a form which is consistent with the government's approach to assessing the relative capital costs of alternative decarbonisation options from a social perspective (DECC, 2014). It is based on an analysis of 'order of magnitude' option capital costs. The purpose of developing and presenting this cost analysis is to provide an indication of the capital costs for the pathways, which could form a basis for further work.

In gathering capital cost-related data, literature or engagement with stakeholders were used to establish an initial dataset for use in the cost analysis assessment. Operating costs such as energy use changes, energy costs and labour are not included in this analysis, although we recognise that operating costs resulting from the decarbonisation pathways will have a major impact on any economic assessment. For example, some options (e.g. carbon capture and electrification of firing) greatly increase energy use and/or operating costs of a process plant.

4.6.2 Calculation of Pathway Costs

The pathway costs and carbon dioxide savings are measured with respect to the reference trend, i.e. they are calculated as the difference between costs and emissions under the decarbonisation pathway and those under the reference trend. This means the costs represent the additional capital costs for the pathway compared to a future in which there was no deployment of options. The pathway costs have been assembled from the estimated costs of the combination of decarbonisation and energy efficiency options, in accordance with each carbon reduction pathway including the selected deployment rates of each option. The methodology for calculating the total discounted capital costs which produce the CO_2 reductions for each pathway can be summarised as follows:

1. Capital costs of deployment for each decarbonisation and energy efficiency option are calculated based on the order of magnitude capital costs to deploy that option at one site (or installation or unit of equipment). This is then deployed to the applicable number of sites (or installations or units of equipment) for the (sub)sector in the pathway as defined by the model.
2. Capital costs reflect the additional cost of delivering the carbon dioxide and/or energy reduction options compared to continuing production without deploying the options. For a number of major investment options, including replacement of life-expired assets with BAT (for a list of options in this category see appendix C), only a proportion of the cost is assumed to be attributed to carbon dioxide emission or energy reduction, as a significant factor for the investment in this case would be to replace retiring production capacity and to recognise that options may be implemented for reasons other than decarbonisation or energy efficiency. In the absence of detailed information this proportion (attributed to the capital cost calculation in this analysis) is assumed to be 50%. For all other technology options the entire capital cost (i.e. 100%) is attributed to energy or carbon reduction. Capital costs are applied at the year of each deployment step (as modelled in the carbon reduction pathways), and adjusted in cases where the asset life defined in the option register would extend beyond 2050 to reflect their residual value on a linear depreciation basis.
3. The annual capital expenditure of each pathway is calculated from the capital cost and deployment of each of the options selected. Capital costs are presented in present day value (i.e. 2015) and assumed to remain constant throughout the period. The discount rate for costs has been chosen to be 3.5% to value the costs from a social perspective and in accordance with standard HM Treasury methodology for this type of assessment. In other words, all proposed capital expenditure on the

various pathways are adjusted for the time value of money, so costs (which occur at different points in time) are expressed on a common basis in terms of their ‘net present value’ using the discount rate of 3.5%. The effect of this standard methodology is to reduce the apparent cost of large investments that are deployed in the pathways later in the study period.

The following specific assumptions apply:

i. Asset replacement is assumed to take place at end of life of an existing asset. No allowance has been made for loss of production during the shutdown period associated with the implementation of major and/or disruptive technology options. Similarly no allowance has been made for loss of EU ETS allowances or civil works associated with a major shutdowns and plant rebuilds. Although costs may be incurred in a case where a plant is written off before the end of its life, this has not been taken into account in this analysis.
ii. It has been assumed that minor incremental improvements would be implemented in the shadow of other rebuild or maintenance work so that no additional costs for shutdown would be incurred.
iii. No allowance has been made for the costs of innovation and it is assumed that the costs of development of breakthrough technologies would be funded separately and not be charged to subsequent capital investments. Technology licensing costs are assumed to be included in the capital costs.
iv. No carbon price or other policy costs are included in the calculations.
v. Changes in other operating costs including labour, maintenance or consumables associated with the deployment of options have not been included (although it is noted these will be significant for many options).
vi. This analysis covers capital costs for carbon reduction: changes to energy use and energy costs (as a result of deployment of the options) has not been quantitatively included although it will be significant for many options.

4.6.3 Limitations

The project methodology for cost data collection and validation did not deliver a complete dataset for the capital cost of options, and where data was available, it was qualified at low confidence levels. Further, estimates based on expert judgement have been made where data gaps remained. Also, the degree of stakeholder engagement in relation to this cost analysis was lower than for the carbon reduction pathways.

All costs in the data input tables are subject to wide variation, for example between sites and sub-sectors and for technology options that have not been demonstrated at commercial scale. Hence, the cost data represent ‘order of magnitude’ estimates that require extensive further development and validation prior to any further use, including with sector stakeholders.

Moreover, the assumptions and constraints on confidence levels limit the valid uses for the results of this cost analysis, therefore the following applies to use of this analysis:

- The values are a starting point to help assess relative benefits of different technologies over the long term.
- The cost analysis results should not be used in isolation to compare decarbonisation technologies or decide on priorities for their development – additional techno-economic analysis should be carried out on individual options or groups of options.
- The cost analysis is part of a process of research and exploration and is being shared in a transparent way to support the development of broader strategy. The results are effectively provisional order of magnitude estimates which need to be developed further on the basis of thorough research before they can be used to inform decisions.

4.6.4 Cost Analysis Results

The results of the cost analysis of decarbonisation for the various pathways within the current trends scenario are summarised in Table 14: Summary costs and impacts of decarbonisation for the pathways below.

Results can be used for relative comparison between pathways in a sector. No cost moderation process between the eight sectors has been carried out and therefore in the absence of further data validation and analysis comparison between sectors is not recommended.

The carbon dioxide emission abatement offered by each pathway has been totalled for each year to present a **cumulative** carbon abatement figure for the period from 2013-2050 compared to the reference pathway.

Although this analysis of discounted capital cost does not include energy costs, it should be noted that energy cost changes will be subject to the uncertainties of future energy cost projections and the significant divergence between energy costs applicable to the different levels of energy consumption. A high level qualitative assessment of the impact of energy use and cost is presented in the table below.

Pathway	Total Discounted Capital Cost 2014-2050 (million £)[14]	Cumulative CO_2 Abated 2014-2050 (million tonnes CO_2)[15]	Projected Impact on Fuel or Energy use and Fuel or Energy cost
BAU	30	7.7	This pathway includes deployment of options that increase overall energy efficiency and reduce overall fuel use. In the period 2014-2050, this pathway would result in an overall reduction in energy and fuel used. The projected value of this saving will depend on the fuel cost forecast adopted.
40-60%	70	14	The increase in fuel costs from the substitution of natural gas with electricity for electric melting is projected to be off-set by the reduced cost of natural gas consumption from energy efficiency measures. The overall net effect would depend on the fuel cost forecast adopted.
60-80%	100	18	
Max Tech without CCS	150	22	The main characteristic of this pathway is a projected significant transfer of energy use from natural gas to electricity resulting in a very large overall increase in energy use and costs. The scale of the increased cost would depend on the fuel cost forecast adopted. Fuel switching (biogas) is also an important option in this pathway
Max Tech with CCS	150	19	The carbon reduction in this pathway includes carbon capture and electric melting, both of which would increase energy use, a very large overall increase in energy use and costs is projected. The scale of the increased cost would depend on the fuel or electricity cost forecast adopted.

[14] Model output rounded to 1 significant figure to reflect 'order of magnitude' input data
[15] Model output rounded to nearest million tonnes of CO_2

Table 14: Summary costs and impacts of decarbonisation for the pathways

4.7 Implications of Barriers and Enablers

From the pathways described above, there are a number of options that will need to make significant contributions to decarbonisation under some or all of the pathways and scenarios. These are:

- Recycling (cullet)
- Improved process control
- Waste heat recovery for raw materials pre-heating
- Oxy-fuel combustion
- Batch pelletisation
- Electric melting
- Batch reformulation
- Fuel switching
- Carbon capture for utilisation or storage,
- Waste heat recovery
- Conventional improved furnace construction
- Innovative improved furnace construction

From the evidence gathered during the project (from literature, interviews, workshops, and expert technical advice from British Glass) there are a number of barriers and enablers associated with these options. These are discussed below.

4.7.1 Recycling (Cullet)

This option relates to the increased use of cullet for melting rather than making glass from raw materials.

The industry is already using cullet (which significantly reduces process emissions), but increasing this cullet use would require an increased quantity and quality of the available cullet. Currently, the available cullet often does not have the required quality to re-melt in the glass manufacturing process. High-quality cullet would require colour separation and removal of different contaminations such as metals, lead and aluminium (from double-glazed units), as well as a separate collection of different types of glass. Currently, there is no infrastructure for flat glass recycling. These and other collection issues result in a lack of supply of good-quality cullet, which is a barrier to decarbonisation of the UK glass sector.

A better separation system of recycled glass, more RD&D, the collection of building waste and the careful dismantling of flat glass could enable increased use of cullet. The amount of available cullet could also be increased by importing cullet. Another enabler for increasing cullet use would be the education of container glass users to accept less clear products: a lot of glass applications could easily be switched from clear to green or brown containers, or clear glass of lower quality could be utilised; for example some clear glass bottles in some European countries have a green tint, but workshop participants advised that this quality of bottle is currently not accepted in the UK for comparable applications, in some cases by the same customers.

For the current trends scenario, the increased cullet option has the biggest impact on the BAU pathway.

Enablers	Better separation of recycled glass Improved technology of cullet suppliers Increased cullet availability Container glass users educated to accept less clear product Incentive of recycling flat glass during vendor replacement Government policy to provide more clarity for local authorities' policies

	Education of consumers to recycle more Funding for further studies and infrastructure development
Barriers	Lack of availability of recycled glass (cullet) in the UK Lack of quality of available cullet (contamination with metal or stones, different colours of glass, etc.) Lack of recycling infrastructure for non-domestic recycling (e.g. recycling windows from buildings) Difficulty of collecting from city centres and apartment blocks Lack of low-iron cullet Limits of cullet processing technology

4.7.2 Improved Process Control

This option relates to the use of process control strategies to control energy consumption through controlling complex and inter-related process activities.

One enabler would be access to knowledge, showing evidence of success or a suppliers' benchmark. Together with alternative financing, improved process control would be implemented more easily, as it is a proven technology and results in cost savings once the process is better controlled.

It is, however, difficult to show how effective this technology really is because it is hard to measure the energy saving benefits. Moreover, retrofitting of improved process control technologies is often difficult, limiting this option to installing control systems when new equipment is being installed. These and other barriers hamper the deployment of improved process control.

This option impacts all pathways.

Enablers	Cost savings once process is better controlled Proven technology Access to knowledge Grant funding and alternative financing with low interest rates Technical development of better sensors
Barriers	Completion of process monitoring improvements not cost-effective Difficult to measure energy saving benefits Retrofitting difficult Payback unknown and high costs Visibility of full process and energy flows not always optimised Reactive maintenance programs Skills and resources on-site to man the system Supplier or contractor choice

4.7.3 Waste Heat Recovery for Raw Materials Pre-Heating

This option involves using pre-heaters which use hot furnace waste gases to warm the batch and cullet to temperatures of 275-325°C. Pre-heaters can be designed for cullet, batch or a mixture of the two. Fuel-based CO_2 emissions would fall in proportion to the fuel savings (15%).

The main barrier to this option is the existing technology, which is currently only applicable to high cullet percentages in the feed. Therefore, a consistent cullet supply is needed, referring back to the issue of available high-quality supply. SORG is, however, currently developing a new technology that should also be able to pre-heat feeds with low cullet percentages, which could enable the uptake of waste heat recovery for raw materials pre-heating.

Other barriers for this option are the high capex, the space limitations on existing sites and the fact that retrofitting on existing plant layouts presents technical challenges and therefore furnace rebuild is often required to allow for raw material pre-heating using waste heat.

Under current trends, this option would impact all pathways, with the biggest impact on the 40-60% CO_2 reduction pathway.

Enablers	Grant funding, and alternative external financing with low interest rates SORG developing technology for low cullet percentage
Barriers	Not currently applicable to low cullet percentages Retrofit difficult capex high Space limitations

4.7.4 Oxy-Fuel Combustion

This option involves increasing the percentage of oxygen in the furnace which makes the furnace more thermally efficient and therefore use less fuel. The technology is widely used in fibre glass production and some specialist applications in container glass.

Using oxy-fuel combustion reduces electricity costs, and holds the potential for 'over the fence' oxygen supply, i.e. with the oxygen plant owned and operated by a third party who sell the oxygen to the glass factory. As the technology is widely used in fibre glass production, the technology is proven, although uptake could be further enabled by a pilot plant for flat glass production. Another enabler for this option is the compliance with NO_x emissions legislation.

The main barrier for deployment of this technology is the energy and costs required to produce oxygen, as oxygen generation will require electricity. The capex for this technology is also high, taking into account plant infrastructure, burner technology, furnace design, regenerators, pipework and cryogenic systems, resulting in extended payback periods. Currently, no public funding incentive exists for oxy-fuel combustion technologies.

This option impacts all pathways under the current trends scenario, but mainly the Max Tech pathway with CCS/U.

Enablers	NO_x emissions legislation Pilot on flat glass Reduced electricity cost Potential for 'over the fence' O_2 supply
Barriers	Increased CO_2 and increased cost of electricity due to O_2 use High capex 2-4 years typical payback Lifespan of existing furnace

4.7.5 Batch Pelletisation

This option involves producing a pre-mixed pellet with each pellet comprising the correct proportions of ingredients. Pellets are quicker and easier to melt than loose powder, allowing more time for the refining process and leading to better glass quality.

Batch pelletisation would require an extra step in the production process, making glass manufacturers reluctant to implement this option. Production of pellets involves extra costs for binders and water, and requires a re-investment in on-site technology. The payback period is high, and the extra costs versus energy savings are questionable. A full-scale trial of batch pelletisation could enable the uptake of this option.

For the current trends scenario, the batch pelletisation option has the biggest impact on Max Tech 2 and the 40-60% CO_2 reduction pathways.

Enablers	Full scale trial
Barriers	Another step in the production process Payback Extra costs versus energy savings are questionable Reduced production flexibility

4.7.6 Electric Melting

This option involves using an all-electric furnace to melt glass. Electrical furnaces are more thermally efficient as they produce no hot waste gas products.

To enable electric melting, more RD&D and demonstration projects are needed, and the realisation of self-generation of power would also act as an enabler. Electric furnaces are cheaper to build and allow for a flexible operation. A guarantee on the emission related production and CO_2 or energy reduction credits would enable a further uptake of this technology. Generation of electric power on-site, through renewables generation could provide a small proportion of the electrical power requirement, potentially at lower cost and at lower carbon intensity than grid electricity supply.

Barriers to electric melting include concerns on the level of grid decarbonisation, high electricity prices (compared to natural gas), reliance on one energy source and the rapid wear rate of refractories.

This option would have an impact on all pathways, but is of prime importance to the Max Tech pathway without CCS/U.

Enablers	Upscale RD&D Self-generation of low cost, decarbonised power CO_2 or energy reduction credits Low energy losses Guarantee on emission related production Flexibility of operation
Barriers	Concerns on level of grid decarbonisation High electricity price Furnace life and replacement cost Rapid wear rate refractories Batch cost Reliant on one energy source Technology not proven at scale for major glass types Availability of secure and affordable electricity in the UK

4.7.7 Batch Reformulation

This option involves adding small quantities of more innovative materials which can allow the melting or mixing process to proceed at lower temperatures and with the reduced fuel consumption. Alternatively, existing raw materials could be de-carbonated so no CO_2 is produced during the glass making process.

Potential barriers regarding batch reformulation include the need for refractory material to survive different glass compositions, possibly affecting the furnace life. Cost for energy, material, transport and chemical preparation would be high, and expectations of optional quality are thought to be unrealistic. Moreover, alternative materials might not be available, and alternative furnace design may be required.

This option would have an impact on all pathways, but would influence the BAU the most.

Enablers	Long-term performance RD&D funding, academic research
Barriers	Furnace life Cost Resistance to change Unrealistic expectations of optional quality Alternative furnace design may be required Lack of alternative raw materials

4.7.8 Fuel Switching

This option involves switching fuels to alternative fuels such as bio-methane derived from the gasification of biomass on site, which is fully interchangeable with natural gas. Solid fuels are not viable for glass making due to the ash affecting the colour of glass, and use of hydrogen presents too many technical difficulties due to the significant differences in combustion properties and flame luminosity/flame temperature between natural gas and hydrogen which make hydrogen combustion unsuitable for heating glass furnaces.

Availability of biomass is a concern, as it is a sought-after alternative fuel in several industries as well as for power generation. In addition, since biomass must be gasified to provide biogas fuel (i.e. bio-SNG) in the glass sector, it may be preferentially utilised in sectors that can use it directly as a substitute solid fuel.

This option would only have an impact on the Max Tech pathway without CCS/U.

Enablers	Availability of affordable and sufficient alternative fuels RD&D funding, academic research
Barriers	Technical viability Availability in secure and sufficient quantities Higher costs Prices: if alternative fuel is available, and technology is secure and proven RD&D on combustion of alternative fuels New national infrastructure ‘Green’ electricity production Biofuel: need supply to match demand

4.7.9 Carbon Capture for Utilisation or Storage

This option relates to the capture of carbon dioxide generated by combustion processes. This option could involve either carbon capture and utilisation, which removes the CO_2 emissions from process gases, purifies them if required then passes them on as a feedstock to another user; or carbon capture and storage, which is taking the carbon and storing it underground in suitable geological features.

CCUS can be combined with oxy-fuel combustion. Making a CO_2 transportation network available to tie in to would enable the uptake of these technologies, although they are still facing many barriers (additional energy requirements for carbon capture, plants that are not located within the CCUS clusters will have difficulties to get access to storage facilities, contaminants in flue gas stream, high capex, need for collaboration, etc.).

This option only impacts the Max Tech pathway with CCUS.

Enablers	Combination with oxy-fuel: synergy with gas separation Make CO_2 transportation network available to tie in to RD&D and technology already available: leverage developments in power sector Grant funding, and alternative financing with low interest rates

Barriers	Additional energy required to operate CCUS equipment and more CO_2 emissions generated Plants not located within CCS/U clusters Issues of storage, including long-term liability Location and transport: distance from storage site Funding Demonstration of commercial scale Contaminants in flue gas stream Large capital investment needed Collaboration with others needed Internal capability and knowledge Business value

4.7.10 Waste Heat Recovery – Non-Furnace

This option involves taking waste heat from the glass furnace or smaller other processes such as annealing lehrs or air compressors to maintain adequate warehouse temperatures or use in general heating applications.

There are good suppliers available offering full solutions for waste heat recovery technologies. This, together with cross-sector technology transfer and the availability of a district heat network to use energy, enables the uptake of this option. However, there are often no heat users close to the heat source, requiring significant amounts of ducts and pipes. This results in long payback periods. Moreover, as industry is operating in a different environment, scrubbing of the waste gases would be required, increasing the effort and costs.

This option impacts all pathways.

Enablers	Energy savings or CO_2 reduction Good suppliers with full solution offerings Cross-sector technology transfer Availability of a district heat network to use energy
Barriers	Often no heat required local to the source Long payback Environment is often dirty: scrubbing required Not proven on wide scale Cost: economic case study required Technology availability questionable

4.7.11 Conventional Improved Furnace Construction

This option involves incremental improvements on the original ground-breaking designed furnace. Furnace designers have greatly improved efficiencies and the rate of improvement has slowed.

Improved furnace construction could result in improved product quality and improved payback rates. RD&D and large-scale testing are available, enabling the uptake of these technologies. However, the risk of changing technologies is still perceived as important, thereby hampering the deployment, together with other barriers such as funding and existing infrastructure limitations.

This option impacts all pathways.

Enablers	Funding support for major step changes in technology Large scale testing and RD&D New control technologies Improved quality of products Improved payback rates Grant funding, and alternative financing with low interest rates
Barriers	Risk of change in technology Funding Applicability not known Existing infrastructure limitations Long life cycle Still under research

4.7.12 Innovative Improved Furnace Construction

This option involves developing innovative alternative designs to the regenerative tank furnace which was developed in 1873.

Currently, more and more suppliers are focussing on energy and emission reducing technologies, transferring proven results and thereby enabling the uptake of more innovative furnace technologies. Still many Barriers to the uptake exist, including financial constraints, conservative suppliers, risk of being the first mover, high payback periods, and glass quality issues.

This option impacts the more advanced pathways like the 60-80% CO_2 reduction pathway and the Max Tech pathways.

Enablers	More suppliers focussing on energy and emission reduction technologies Small improvements to improve heat distribution in furnace Grant funding, and alternative external financing with low interest rates Transfer of proven results
Barriers	Financial constraints Conservative suppliers Risk of being first mover on a 10 year+ investment Need to significantly improve firing and homogenisation times Large investment Glass quality issues Payback 15-20 years

4.7.13 Others

The sections above focus on the options that provide the most significant decarbonisation potential and their associated barriers and enablers. From the evidence gathered as part of this roadmap, other options share many of the same enablers and barriers such as:

- Alternative financing needed to help overcome longer payback periods of advanced technologies.
- High levels of competition amongst glass manufactures limits collaboration in piloting advanced technologies.
- External finance providers, including the Green Investment Bank, charge high rates of interest making this unattractive for businesses. Businesses would prefer grants or simple schemes to help make environmental projects more financially viable.
- Major innovative technology changes require significant further development before they could be considered for deployment.

- A number of technologies (such as CCS/U) are likely to result in higher overall energy use and therefore higher operating costs.
- Long-term stability in carbon pricing is needed in order to make major investments.

Finally, even though decarbonised grid electricity is included in all pathways and is not under the direct control of the sector, it is a major contributor to decarbonisation.

5. CONCLUSIONS - PRINCIPAL QUESTION 6

This section provides assessment of the questions under principal question 6: 'What future actions might be required to be taken by industry, government and others to overcome the barriers in order to achieve the pathways in each sector?'

The section is structured as follows:

- Eight 'strategic conclusions' or themes have been developed by analysing the main enablers and barriers. Example next steps/potential actions are also included for each strategic conclusion.
- Six key technology groups are discussed, many of which link to the themes above. As described in section 4, a small group of technologies make a significant contribution to decarbonisation in 2050, especially for Max Tech savings[16]. Example next steps are included to assist with developing, funding and implementing the technologies.

It is intended that government and industry use the roadmap to develop and implement an action programme in support of the overall aim of decarbonisation while maintaining competitiveness in the sector.

5.1 Key Points

During the development of potential pathways to decarbonisation, the barriers to their implementation and enablers to promote them were summarised in section 3.4.5. Having cross-referenced the enablers and barriers through three different research methods (see section 2.2.1), we have summarised the key points in key themes (strategic conclusions) and key technology groups.

Strategic Conclusions

Strategy, Leadership and Organisation

Strategy is important in any industrial sector or company in that it provides long-term aims and a plan of action of how to achieve the aims. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis. In order to take this agenda forward, it is considered critical that the glass sector, government and other stakeholders recognise the importance of strategy and leadership in the context of decarbonisation, energy efficiency and competitiveness for the sector.

Business Case Barriers

Decarbonisation requires expensive investment and there is a risk that companies may simply not be able to afford it. Significant improvement in the investment environment would be required to permit the necessary surge of investment likely to be required in the sector to deliver future options contributing to decarbonisation and energy efficiency. RD&D, demonstration and deployment of major technologies requires significant upfront capital which is not always readily available in the UK glass sector, due to internal competition with projects that may have higher business priority or shorter payback times. Projects that appear to be economically worthwhile in isolation may not be implemented, even if a solid and well-justified business case is made. With respect to external financing, the evidence suggests that this is not always available on terms (e.g. interest rates) that allow internal investment criteria to be met.

[16] These technology groups apply to the glass sector and also the other seven sector roadmaps.

Future Energy Costs, Energy Supply Security, Market Structure and Competition

It is critical to ensure that future decarbonisation and energy efficiency actions maintain the position with respect to overall cost-competitiveness of the UK sector compared to competing businesses operating overseas. Energy security and energy cost comparison to other regions (both reality and perception), are important when investment decisions are made. There is a role for government in recognising the importance of and link between long-term plans on energy security to investment decisions made by companies in the UK glass sector.

Companies are not able to recover the cost of investment because consumers are not perceived to be currently willing to pay higher prices for low-carbon products. Additionally, if operating costs for UK companies rise too high, they will be unable to compete against foreign made products. Some of the key technological options considered by the pathways, such as CCS, may require higher energy consumption and thus increase operating costs, which will reduce the overall cost-competitiveness of the sector compared to businesses overseas.

Industrial Energy Policy Context

Many in the sector have emphasised that the need for a long-term energy and climate change policy is key to investor confidence, according to literature and other evidence-gathering sources (see 3.4.5 'Enablers and Barriers'). There is a need for long-term certainty around policy support for decarbonisation and energy efficiency, as changes in policy (around incentive schemes) can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy prices.

Life-Cycle Accounting

The interaction between sectors is significant, with the carbon emissions of the glass sector being necessary to make products that reduce carbon emissions in other sectors. For example, energy efficient flat glass for windows is a more complex product than normal glass, and requires more energy to manufacture. However, when installed as an energy efficient window in a building, this will save more energy in use (compared to normal glass) than the total energy required to manufacture the glass.

Value Chain Collaboration

There is an opportunity for the sector to reduce carbon emissions by increasing the use of recycled glass (cullet). Closed loop recycling (recycling glass back to glass) results in greater energy efficiency and CO_2 reduction than using recycled glass as aggregate.

The majority of customers and consumers would not preferentially choose a low carbon product over a similar product manufactured to lower environmental standards. If consumers were willing to pay extra for low-carbon products, this could help fund energy efficiency and CO_2 reduction. Creating markets for low carbon glass products could improve the business case for investing in additional environmental projects

Research, Development and Demonstration

Many of the options identified in the pathway analysis require development of new technologies and processes. The interviews and workshops have identified that progressing the necessary RD&D into decarbonisation technologies is an important enabler. There is also a need to support funding of these activities (links to the policy and finance themes). Creating an enabling environment is primarily related to actions that can be taken by industry, government, and other stakeholders to help progress decarbonisation technologies and improve market demand for 'greener' glass products.

People and Skills

There is a limited number of staff with specialised skills in energy and furnace engineering in the sector. The priorities of those staff tend to be on ensuring compliance with regulations which diverts attention and effort away from identification and implementation of energy efficiency opportunities.

Key technology groups

Electricity Grid Decarbonisation
Low-carbon energy supply is critical to the glass sector and actions are required to maintain a competitive position for the UK. Certain options, such as electric melting, will not reduce carbon emissions without grid decarbonisation. Actions will be required to ensure that this takes place while maintaining cost-competitiveness. The Government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

Electrification of Heat
Electric melting is a key decarbonisation technology, and is assumed to be available for commercial implementation post-2030. The main barriers to implementation appear to be some late state research and development needs including scale-up, the current carbon intensity of the UK electricity supply meaning that electric melting has a higher carbon impact than conventional natural-gas fired furnaces and the current and projected high cost of electricity compared to natural gas.

Fuel and Feedstock Availability (including Biomass)
Understanding how much low-carbon fuel and feedstock will be available to the sector is an important first step in addressing a key barrier to the pathways that include the use of (on-site generated) biogas or bio-methane as a fuel substitution option for glass melting. At present, as identified in the sector workshops, there is a lack of clarity on the long-term availability, cost and technical viability of resources such as biomass and the degree to which it can be considered low carbon. It will also be necessary to understand, both within the glass sector, other industries and across the wider economy, where these fuels and feedstock can be used to achieve the greatest decarbonisation impact (links to Life-cycle carbon accounting above). There is significant added value to use biomass for heat and power (via CHP technology) compared to power generation only, and this is recognised in government electricity market support policy.

Energy Efficiency and Heat Recovery
Energy efficiency and heat recovery technologies have been identified in the roadmap as a significant potential contributor to decarbonisation. This option covers a group of technologies which are generally well-established and so there is a relatively low technical risk with their implementation. By reducing energy use, these options can provide operational cost savings. Waste heat recovery is already practiced by the glass sector, but further opportunities exist and, in addition, waste heat can be utilised for electricity production. The main barriers are high capital costs of equipment, long paybacks, practical and technical issues.

Carbon Capture
Carbon capture has a large emissions reduction potential, however; it also has many barriers that need to be overcome before it can be viable. Glass companies expressed a preference to avoid carbon capture in favour of other decarbonisation technologies because of perceived cost and disruption of carbon capture equipment and its mutual exclusivity with electric furnaces. However, if other options cannot be implemented, then it may be necessary for the glass sector to implement carbon capture, and it is therefore important that the technology option is not ignored, and the potential implementation of carbon capture given consideration.

Recycling
Increasing the proportion of recycled glass (cullet) used as raw material in the glass sector would significantly reduce the overall CO2 emissions from the industry. What is required to achieve this is a recycling system that can deliver both the quantity and quality of cullet required for the production of all grades of container and flat glass.

The scale of CO_2 emissions in the glass sector is such that the implementation of carbon capture at a glass manufacturing site would be insufficient to justify the implementation of a full CCS chain. This can be addressed if the glass facility is located within a larger industrial cluster to access a shared CO_2 transportation and storage network or by implementing utilisation of captured CO_2 (CCU) rather than storage. The smaller volumes of CO_2 captured when compared against other emitters are more likely to align with the CO_2 feedstock requirements of future CO_2 utilisation industries.

5.2 Strategic Conclusions

5.2.1 Strategic Leadership, and organisation

Strategy is important in any industrial sector or company in that it provides long-term aims and a plan of action of how to achieve the aims. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis. In order to take this agenda forward, it is considered critical that the glass sector, government and other stakeholders recognise the importance of strategy and leadership in the context of decarbonisation, energy efficiency and competitiveness for the sector. This links to all other conclusions below.

A possible action to address this issue is to set up a government-industry working group with responsibility for the glass sector strategic priorities. This group could bring:

- Leadership and vision to the UK sector, emphasising how glass production adds strategic value for the UK and why it is important to face the challenges and develop the opportunities for the sector (this was highlighted by senior stakeholders at the workshops).
- A high level link between industry, government and the EU and a clear framework within which production, technology, energy efficiency and decarbonisation agendas can be taken forward. Members of the working group could engage with executives in corporate headquarters to better inform the UK glass sector strategy.
- A means to take forward the roadmap agenda with shorter term action plans, for example, in five year intervals.

This conclusion is also applicable to individual company strategy, where companies have a key role in overcoming barriers to and strengthening enablers for decarbonisation and energy efficiency.

5.2.2 Business Case Barriers

The pathway analysis indicates that significant improvement in the investment environment would be required to permit the necessary surge of investment likely to be required in the sector to deliver future options contributing to decarbonisation and energy efficiency.

A key theme from the evidence in the interviews and workshop is that the RD&D, demonstration and deployment of major technologies requires significant upfront capital which is not always readily available in the UK glass sector. This may be because a company simply cannot afford it. Or it may be due to internal competition with projects that may have higher business priority or shorter payback times, and this applies to all projects from small-scale energy efficiency improvements up to major new or replacement plants. This competition is generally for resources of all kinds e.g. capital, technical staff and management time. For these reasons, projects that appear to be economically worthwhile in isolation may not be implemented, even if a solid and well-justified business case is made.

With respect to external financing, the evidence suggests that this is not always available on terms (e.g. interest rates) that allow internal investment criteria to be met. Examples of actions to overcome these issues include:

- Funding: government to identify and allocate funding in key areas. Industry to investigate and procure financing for glass projects
- Industry to investigate working with third parties such as OEMs and ESCOs and their financial support
- Government to explore creating incentives which will encourage companies to invest in decarbonisation measures, e.g. for waste heat recovery technologies, energy efficiency and renewable energy generation on-site.
- Finance mechanisms: Government to assist in developing external project financing mechanisms. This could include enabling funding to be made available from the Green Investment Bank. These need to take account of the likely long-term nature of energy saving projects.
- Industry to use a full range of outputs from other actions in this section to make the strongest possible internal business cases for decarbonisation investments. This will need to be an on-going activity.
- A clear explanation of state aid, funding, and subsidy in relation to energy policies.

5.2.3 Future Energy Costs, Energy Supply Security, Market Structure and Competition

It is clearly critical to ensure that future decarbonisation and energy efficiency actions maintain the position with respect to overall cost-competitiveness of the UK sector compared to competing businesses operating in other part of Europe and other regions globally. This strategic conclusion links to a number of external factors that influence the business environment in which the sector operates. These include energy security and energy cost comparison to other regions (both reality and perception), as these factors are important when investment decisions are made (see section 3.4.3). There is a role for government in recognising the importance of and link between long-term plans on energy security to investment decisions made by companies in the UK glass sector. Moreover, in addition to energy security, the cost and carbon intensity of energy in the UK will influence company decisions to invest in the sector (an important example of electricity supply security, cost and carbon intensity).

Companies are not able to recover the cost of investment because consumers are not currently willing to pay higher prices for low-carbon products. Additionally, if operating costs for UK companies rise too high, they will be unable to compete against foreign made products.

Some of the key technological options considered and discussed by the pathways in section 4, such as CO_2 capture, require higher energy consumption and thus increased overall cost. This would reduce the overall cost-competitiveness of the sector compared to competing businesses operating overseas, e.g. Asia. This could in turn reduce the attractiveness of the sector in the UK for future investment.

With regards to the competitive markets in which the sector operates, as highlighted in section 3, this can be a barrier to collaboration on sharing best practice. Example actions to strengthen sharing of best practice are the use of benchmarking systems, better sharing of expertise and skills across the sector, so that that cost of innovation can be shared across multiple companies, pre-competitive joint funding of development projects and review of competition rules sharing business information (specifically relating to decarbonisation and energy efficiency – see also research, development and demonstration)

5.2.4 Industrial Energy Policy Context

Many in the sector have emphasised that the need for a long-term energy and climate change policy is key to investor confidence, according to literature and other evidence gathering sources (see 3.4.5 'Barriers and Enablers'). There is a need for long-term certainty around policy support for decarbonisation and energy efficiency, as changes in policy (around incentive schemes) can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy prices. The availability of low carbon, affordable electricity and biofuels are key enablers for glass sector decarbonisation.

Example actions that would partially mitigate this include:

- Government to consider policies to prevent carbon leakage. Work on this should start now on the assumption that it will take a number of years to implement and many of the decarbonisation options in the pathways depend on investment that needs this to underpin them.
- Establish a ‘level playing field’ through a global carbon agreement.
- Government to explore alternative funding arrangements to recognise mid- to long-term decarbonisation benefits. This would allow the value of these benefits to be taken into account in investment decisions. An effective carbon price would be one means of doing this.
- Government to put an industrial strategy in place to give confidence that the industry will be here in 20+ years. This confidence would in turn facilitate future investment in both current and new plants.
- Review planning requirements for industrial renewable energy and low-carbon projects where clear benefits to decarbonisation or energy efficiency, competitiveness and local economy are proposed.

The possible ways forward outlined above to implement effective long-term carbon pricing would have an impact throughout the supply chain. This links to the business case barrier theme above.

5.2.5 Life Cycle Accounting

The interaction between sectors is significant, with the carbon emissions of the glass sector being necessary to make products reducing carbon emissions in other sectors. For example, high energy efficiency flat glass for windows is a more complex product than normal glass, and requires more energy to manufacture. However, when installed as an energy efficient window in a building, this will save more energy in use than more energy in use than the total energy required to manufacture the glass[17].
Examples of potential next steps include:

- Lifecycle / holistic consideration of such activities to ensure that policies and investments are focussed on the most effective decarbonisation measures overall; so for example, there isn’t a disincentive at factory level for using more energy to manufacture energy efficient products which result in greater overall emissions reductions.
- LCA is one method which attempts to scientifically analyse part of this bigger picture. LCAs for glass products are being developed across Europe, but LCA does have limitations. For example, it is still can’t be used to reliably compare the environmental impact of different materials because the boundary conditions for each material are so different.
- Government to explore how policies in linked areas could contribute towards reducing national CO_2 emissions, for example, it has been calculated by the National Energy Foundation if more energy efficient glazing is installed in existing UK buildings, this would save 48,348 GWh/yr and 8.7 Mt/yr CO_2 – this is 14 times more CO_2 than is produced by flat glass factories. Also, encouraging the uptake of light weight bottles, windscreens and fibre glass vehicle parts would reduce CO_2 emissions from transportation. Participants at the workshop suggested that the potential to increase the use of reusable bottles in place of single use could be investigated. While the CO_2 emissions per unit is likely to increase (since greater strength, and hence heavier bottles, would be required), overall emissions would need to be assessed to quantify the potential benefits of this approach.

[17] See http://www.glassforeurope.com/en/issues/faq.php#3

5.2.6 Value Chain Collaboration

Recycling

There is a significant opportunity to engage with customers, government, local authorities, construction companies, builders and vehicle manufacturers on the recyclability of glass. Specific challenges include:

- Quality of cullet
- Quantity of cullet
- Competition from aggregates producers
- Immature recycling infrastructure in some parts of the country and for certain waste streams e.g. commercial waste
- Limited recycling of flat glass
- Supply chain education

The following possible actions could be developed to support decarbonisation from increased use of cullet:

- Increased communication between waste companies, DEFRA, DCLG and the sector to ensure that there is a consistent recycling system across the country including a recycling infrastructure plan.
- Government, glass manufacturers, glass customers, recyclers and municipal recycling facilities (MRFs) and suppliers could come together to investigate ways to improve the recycling infrastructure with the objective of producing increased quantities of high quality cullet. Local authorities should have clarity on waste policies and support domestic and commercial recycling. British Glass has made a good start to this process, but further collaboration with the stakeholders is required to drive this forward.
- An economic study could be implemented to explore the opportunities for glass recycling to identify the 'big wins' and consumer choices (various glass colours, marketing versus customer expectation).
- Improving the amount of flat glass recycled through regulation (perhaps using ELV as an example), and by development of a system to take recovered glass, clean it and transport it to a place where it can be recycled in a cost effective way. One option would be to impose a levy on each window or a deposit scheme where the money goes towards end-point recycling. Various issues need to be overcome, e.g. life span of windows and who takes responsibility for recycling.
- Promoting the need to recycle and collect a cleaner waste stream.
- More stringent regulations on recycling, for example bringing forwards targets for increasing recycling at 90% in 2030 to 90% in 2020, banning recyclables in landfill or creating penalties for those not meeting targets or incentives to increase recycling.
  Improving sorting of mixed waste so it provides lower cost, higher quality cullet in collaboration with other material sectors.

Create Markets for Low-Carbon Glass Products

In the workshops, it was commented that the majority of customers and consumers would not preferentially choose a low carbon product over a similar product manufactured to lower environmental standards.

If consumers were willing to pay extra for low-carbon products, this could help fund energy efficiency and CO_2 reduction. Creating markets for low carbon glass products could improve the business case for investing in additional environmental projects.

Examples of actions to overcome these issues include:

- Government to preferentially purchase low-carbon products to kick-start the market.

- Building on experience with bottled ales, there is an opportunity to negotiate with brand managers and promote less carbon intensive products across the lifecycle with end customers, for example: light weight bottles, reusable bottles, light-weight windscreens and light weight fibre glass vehicle parts. Note that the CO_2 emissions reduction resulting from these actions are not currently attributed to the glass sector.
- Customer education is vital; changing an apparent misperception that thin, light glass is poor quality.
- Develop a similar proposal to the Environmental Product Declaration (EPD) in Germany.
- Labelling and marketing campaigns could be used to encourage uptake of low carbon products.

5.2.7 Research Development and Demonstration

Many of the options identified in the pathway analysis require development of new technologies and processes. The interviews and workshops have identified that progressing the necessary RD&D into decarbonisation technologies is an important enabler. There is also a need to support funding of these activities (links to the policy and finance themes).

Creating an enabling environment is primarily related to actions that can be taken by industry, government, and other stakeholders to help progress decarbonisation technologies and improve market demand for ‘greener’ glass products. Based on an assessment of evidence from interviews and workshops, the following issues have been identified regarding creating an enabling environment:

- Evidence from pathways indicates that Research, Demonstration and Deployment (RD&D) in technology and collaborating to pilot new technologies is required to reach higher decarbonisation levels.
- Glass manufacturers prefer to be the first follower, rather than the leader due to the risk and high cost of failure. Thus there is a potential role for government, industry sectors associations, suppliers and external entities to help the sector collaborate through demonstration projects.
- The interviews identified that RD&D budgets for many glass manufacturers have declined. There is a potential for cross-sector, government, supplier and external entity support for RD&D to spur further innovation.

Specific sectorial decarbonisation technology issues unique to the sector including:

- Research to enable advances in glass composition to enable less energy-intensive processes to be employed. e.g. shorter, lower temperature or reduced number of melting steps.
- Demonstration of new technologies, for example at test facilities, to reduce the risk of damage to commercial plants and encourage uptake.
- Demonstration of electric melting, including scale-up of electrically heated furnaces to commercial scale and actions within the power generation sector to make low carbon electricity available and more competitive as a heat source.
- Development of innovative technologies to enable step changes in furnace design. Several potential technologies have been identified and are at early stages of RD&D; facilitating the progression of these technologies through support mechanisms will maximise the potential for commercial breakthrough.
- Substituting biogas, syngas and hydrogen for natural gas in furnaces. Key areas of research would include the development of advanced biomass gasification technology and the development of burner and furnace technologies to facilitate the use of hydrogen-containing fuel gas within glass furnaces.
- Development of waste heat recovery technologies that can operate using less cullet.
- Successful development and demonstration of CO_2 capture with oxy-fuel combustion within the glass sector.

5.2.8 Employees and Skills

As identified in the workshops, there is a limited number of staff with specialised skills in energy and furnace engineering in the sector. The priorities of those staff tend to be on ensuring compliance with regulations which diverts attention and effort away from identification and implementation of energy efficiency opportunities. Some examples of actions include:

- Better sharing of expertise and skills across the sector, (nationally and internationally) so that that cost of innovation can be shared across multiple companies, and improvements available to all as new best practice.
- A review of what training and skills are necessary to help businesses decarbonise, e.g. writing effective business plans.
- Industry to invest in training and recruitment to make the necessary skills available
- Government to support skills development at a national level

The other actions discussed above aimed at making decarbonisation investment more attractive would also tend to encourage the recruitment of staff with the necessary skills and their use on relevant projects.

5.3 Key Technology Groups

5.3.1 Electricity Grid Decarbonisation

Low-carbon energy supply is critical to the glass sector and actions are required to maintain a competitive position for the UK. Certain options, such as electric melting, will not reduce carbon emissions without grid decarbonisation. The Government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

5.3.2 Electrification of Heat (Electric Melting)

Electric melting is a key decarbonisation technology, and is assumed to be available for commercial implementation post-2030. There are currently no operating plants in the UK but small-scale electrically heated furnaces for the production of speciality glasses are in operation outside the UK. The main barriers to implementation appear to be some late state research and development needs including scale-up, the current carbon intensity of the UK electricity supply meaning that electric melting has a higher carbon impact than conventional natural-gas fired furnaces and the current and projected high cost of electricity compared to natural gas.

Actions which could overcome this include:

- Support for the scale-up, deployment and demonstration of electric melting at large scale in the UK.
- Commit the electricity generation sector to binding decarbonisation targets through to 2050.
- Actions within the power generation sector to make low carbon electricity available and more competitive as a heat source.

5.3.3 Fuel and Feedstock Availability (Including Biomass)

Understanding how much low-carbon fuel and feedstock will be available to the sector is an important first step in addressing a key barrier to the pathways that include the use of (on-site generated) biogas or bio-methane as a fuel substitution option for glass melting. At present, as identified in the sector workshops, there is a lack of clarity on the long-term availability, cost and technical viability of resources such as biomass and the degree to which it can be considered low carbon. It will also be necessary to understand, both within the glass sector, other industries and across the wider economy, where these fuels and feedstocks can be used to achieve the greatest decarbonisation impact.

Possible actions to assess this option further include:

- Investigate the use of (on-site generated) biogas or bio-methane as a fuel substitution option for glass melting. Specifically, chemical composition, impurities and calorific value need to be understood (a 'clean' biogas is required).
- Space availability for biomass gasification units or air separation units at manufacturing sites should be considered when identifying suitable sites for locating/relocating glass making facilities.
- Overcoming barriers to biogas, bio-methane, syngas and hydrogen, such as knowledge gaps around their technical suitability for glass melting (generated on-site via biomass gasification or supplied via the grid) to the sector no later than 2035 for the middle pathway, and 2020 for the Max Tech pathway. This should consider availability and security of supply, cost-effectiveness, and clarity on their carbon intensity and value under the EU Emissions Trading Scheme
- Decarbonisation of the gas grid at national level.

5.3.4 Energy Efficiency and Heat Recovery

Energy efficiency and heat recovery technologies have been identified in the roadmap as a significant potential contributor to decarbonisation. This option covers a group of technologies which are generally well-established and so there is a relatively low technical risk with their implementation. By reducing energy use, these options can provide operational cost savings. Waste heat recovery is already practiced by the glass sector, for example for combustion air preheating, but further opportunities exist within the glassmaking process, including the use of waste heat for preheating batch and/or preheating cullet. In addition, waste heat can be utilised for electricity production, acting to reduce the net electricity imported to the glass manufacturing site. Technologies are available to utilise high-grade waste heat, such as steam generation for use in a steam turbine, low-grade heat, such as the use of organic rankine cycle and advanced technologies including thermo-photovoltaic power generation. Waste heat may also be used as a heat source to generate steam and/or hot water as part of district heating schemes, supplying these as heating media to the surrounding community (residential, commercial or other industry).

The barriers to further deployment of this option relate to the availability of resources (both financial and personnel) to implement them. Example actions to overcome would be similar to those identified above under 'Business Case Barriers' and 'Employees and Skills'.

With regards to waste heat recovery, there is currently a large amount of research and development on-going, but there are opportunities to improve the number and diversity of demonstration projects to recover and use lower grade heat (see also RD&D).

Waste heat is currently not treated as a renewable source and is therefore not eligible for the Renewable Heat Incentive. It is recommended that this is reviewed by government since increase waste heat recovery could bring decarbonisation and competitive advantages (see also section 5.2.4 industrial policy).

5.3.5 Carbon Capture

Carbon capture has a large emissions reduction potential, however; it also has many barriers that need to be overcome before it can be viable. At the workshops, glass companies expressed a preference to avoid carbon capture in favour of other decarbonisation technologies because of perceived cost and disruption of carbon capture equipment and its mutual exclusivity with electric furnaces. The pathways demonstrated that equivalent levels of decarbonisation can be achieved by the glass sector without carbon capture. However, these pathways assume the commercial availability of electric melting, biomass gasification and significantly higher levels of glass recycling. Therefore, if these options cannot be implemented, then it may be necessary for the glass sector to implement carbon capture, and it is therefore important that the technology option is not ignored, and the potential implementation of carbon capture given consideration.

The scale of CO_2 emissions in the glass sector is such that the implementation of carbon capture at a glass manufacturing site would be insufficient to justify the implementation of a full CCS chain. This can be addressed in two ways. Firstly, if the glass facility is located within a larger industrial cluster, then access to a shared CO_2 transportation and storage network would be possible. For any consideration to the future siting or relocation of glass manufacturing facilities, access to CCS clusters should be a consideration. Secondly, utilisation of captured CO_2 (CCU) rather than storage may be an alternative option open to the glass sector. The smaller volumes of CO_2 captured when compared against other emitters are more likely to align with the CO_2 feedstock requirements of future CO_2 utilisation industries. To facilitate CCU, close proximity between the emitter and user is highly advantageous; a future scenario of a glass factory at the centre of a CO_2 utilisation industrial cluster may be foreseen as an optimal approach to the implementation of CCU within the glass sector.

Potential actions to take this technology forward are:

- Industry and government to look into developing collaboration within the sector as well as with other industries to bring carbon capture to demonstration scale within industrial applications to complement existing progress in the power generation sector.
- Develop a plan to implement CO_2 capture technologies for high temperature industries and establish the necessary infrastructure for CO_2 transport to storage or CO_2 utilisation to be available for application in the glass sector by 2025 or 2040 for the Max Tech and middle pathway respectively.
- Investigate flue gas composition so that potential application of CO_2 capture and CO_2 utilisation linked to the glass sector can be better understood, and purification requirements identified. It may be possible to learn from experience in the power generation sector but the differences with glass furnace flue gas need to be characterised.
- Actions to overcome the additional opex and capex of carbon capture plants.
- Space availability for carbon capture plants and associated facilities at manufacturing sites, and proximity of viable off-take for captured CO_2 to the plant location should be considered when identifying suitable sites for locating/relocating glass making facilities.

5.3.6 Recycling

Results from literature, interviews and workshops gave a consistent message that there is an opportunity for the sector to reduce carbon emissions by increasing the use of recycled glass (cullet). Closed loop recycling (recycling glass back to glass) is preferred as it results in greater energy savings and CO_2 reduction than using recycled glass as aggregate.

To increase the amount of glass available to and recycled within the UK glass sector, various barriers need to be overcome. Existing recycling systems could be improved, new glass streams (e.g. building glass) could be recycled, and technologies could be improved to aid processing. The complex situation and economics needs to be studied further to identify constructive ways to move forward.

Over 1 million tonnes of glass was recycled back to glass in the UK in 2012. However, the limiting factor is the availability of competitively priced, uncontaminated recycled glass. If more recycled glass was available in the UK, more could be used in glass manufacturing.

5.4 Closing Statement

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The way in which the report has been compiled is designed to ensure it has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy. It will be successful if, as a result, the government and the glass sector are able to build on the report's evidence and analysis to deliver significant reductions in carbon emissions, increased energy efficiency and a strong competitive position for the UK glass industry in the decades to come.

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7. GLOSSARY

Adoption

The percentage of sector production capacity to which a carbon reduction option has already been applied. Therefore, of the list of options being assessed, this is a measure of the degree to which they have already been deployed in the sector.

Applicability

The percentage of the sector production capacity to which a particular option can be applied. This is a measure of the degree to which a carbon reduction option can be applied to a particular part of the sector production process.

Barrier to Decarbonisation or Energy Efficiency

Barriers are factors that hinder companies from investing in and implementing technologies and initiatives that contribute to decarbonisation

Business as Usual

A combination of carbon abatement options and savings that would be expected with the continuation of current rates of deployment of incremental improvement options in the sector up to 2050 without significant intervention or outside support.

Decarbonisation

Reduction of CO_2 emissions (in $MtCO_2$) – relative to the reference trend for that scenario. When we report carbon dioxide – this represents CO_2 equivalent. However, other GHGs were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site. Also, technical options assessed in this work result primarily in CO2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO2, are very low.

Carbon reduction band or bins

The percentage ranges of CO_2 reduction achieved for a given pathway in 2050 relative to the base year e.g. 20-40% of the base year emission.

Carbon reduction curve or profile

A quantitative graph which charts the evolution of sector carbon emissions from 2014 to 2050

Competition Law

The UK has three main tasks:

- Prohibiting agreements or practices that restrict free trading and competition between business entities. This includes in particular the repression of cartels.
- Banning abusive behaviour by a firm dominating a market, or anti-competitive practices that tend to lead to such a dominant position. Practices controlled in this way may include predatory pricing, tying, price gouging, refusal to deal and many others.

- Supervising the mergers and acquisitions of large corporations, including some joint ventures. Transactions that are considered to threaten the competitive process can be prohibited altogether, or approved subject to "remedies" such as an obligation to divest part of the merged business or to offer licences or access to facilities to enable other businesses to continue competing.

Deployment

Once the adoption and applicability of an option has been taken into account, each option can be deployed to reduce part of the sector's CO_2 emissions. Hence, the deployment of the option from 2015 through to 2050 is illustrated in our analysis by the coloured matrix on the pathway presentations.

Enabler for decarbonisation or energy efficiency

Enablers are factors that that make an investment feasible or would either help mitigate a barrier.

Grid CO_2 emission factor

A specific scenario assumption relating to the average carbon intensity of grid electricity and projection(s) of how this may evolve to 2050

Maximum Technical Pathway ('Max Tech')

A combination of carbon abatement options and savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side. Options selected in Max Tech take into account barriers to deployment but are not excluded based on these grounds. Where there is a choice between one option or another, the easier/cheaper option is chosen or two alternative max tech pathways are developed.

Option

A carbon reduction measure, often a technical measure, such as a more efficient process or technology

Option Register

The options register was developed jointly by the technical and social and business research teams. This was achieved by obtaining the list of potential options from interviews, literature, asking participants at the information gathering workshop which options they would consider viable, and through engagement with members of the relevant trade associations.

Pathway

A particular selection and deployment of options from 2014 to 2050 chosen to achieve reductions falling into a specific carbon reduction band

Projection of Production Changes

A sector specific scenario assumption which defines the changes in production as an annual percentage change to 2050

Reference trend

the carbon dioxide emission trend that would be followed if the 2012 base year emissions were affected by production change and grid decarbonisation in accordance with the sector specific scenarios

Scenario

A specific set of conditions external to the sector which will affect the growth and costs of production in the sector and affect the timing and impact of options on carbon emissions and energy consumption

Scenario assumptions

A set of specific cost and technical assumptions which characterise each scenario. These include forward fuel and carbon price projections, grid CO_2 factor projection and background economic growth rate. The assumptions may include sector forward production projections.

Sensitivity case

The evaluation of the impact of changes in a single assumption on a pathway e.g. the availability of biomass

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