Mapping the flat glass value-chain: A material flow analysis and energy balance of UK production: Appendix

A1: Strategies to decarbonise the glass industry

Summary of British Glass' Net Zero 2050 strategy

		Description and benefits (from [1])	Limitations
Alternative raw material input to reduce process emissions	**Increased use of cullet**	The use of cullet in new production has the benefit of reducing the energy demand as a consequence of reduced furnace operating temperatures. Since the use of cullet reduces the demand for primary materials, CO_2 emissions from carbonate decomposition are also reduced.	There is shortage of good quality cullet for glass manufacture to maximise the CO_2 saving.
	Calcined raw materials and/or alternative raw materials	Calcined materials such as calcium oxide, which is produced from heating limestone to remove the CO_2, could be used to replace carbonates in the batch and reduce site CO_2 emissions. There is on-going research investigating alternative raw materials such as mineral slags, waste incineration ashes and other secondary raw materials. Some of these could be used to replace carbonate raw materials, whilst others may reduce the melting temperature of the glass therefore reducing the energy requirements.	Unless sourced as byproducts from other industries, the use of calcined raw materials will not avoid CO_2 emissions being emitted at some stage in the glass manufacturing value-chain, and potentially create a more inefficient process of decomposition by having to heat the materials twice. The use of calcined or alternative raw materials are in the very early-stages of trialing and will take time to be utilized on a full-scale manufacturing site. Any new material would need to be available in sufficient quantities with no interruption in supply.
Alternative fuel supply to reduce combustion emissions	**Oxyfuel combustion**	Oxyfuel combustion is an established technology which has been successfully implemented in each of the glass sectors. The technology uses oxygen instead of combustion air which gives a furnace energy saving of 10 to 15% and reduces emissions of NOx.	Despite using less natural gas the OPEX costs are higher than for air/ fuel furnaces due to the high cost of the electricity which is used to generate oxygen on-site.
	Liquid biofuels	Replace fossil fuel with bio derived liquid fuels. Natural gas furnace designs can be easily converted to run standard biofuels therefore offering an option to reduce CO_2 emissions using existing furnace technologies. There are suggestions for long-term biofuels to be used in combination with carbon capture and storage.	There is uncertainty over the long-term availability and cost of biofuels. New capital investment may also be required to create fuel storage tanks and pipelines, heaters and pumps to deliver the fuel to the furnace. Carbon capture and storage is not an established technology.
	All-electric melting or hybrid furnaces	All-electric furnaces are an established technology in the glass sector and are more efficient than gas fired furnaces. A hybrid furnace is a furnace could run on 80% electricity with 20% gas energy, with the future opportunity to consider hydrogen combustion. The hybrid furnace approach allows manufacturers to gradually transition to using high proportions of electricity as it becomes more cost-competitive with natural gas. Future designs may also be compatible with hydrogen so that the switch to hydrogen can be made when it becomes available at a particular site.	There is little experience of using all-electric furnace for large scale glass melting such as flat glass where it is thought to be technically challenging to use high levels of electrical boost (>40%). Further development work is required. An interruption in power supply for longer than 2 hours, would cause serious issues and potential loss of the furnace. The site supply would require double circuit security to minimise the risk. In addition, there will need to be investment in the electricity supply infrastructure, and electricity must be cost competitive with natural gas. Currently the high cost of electricity in the UK means that electric melting is not a viable option. Infrastructure – Most sites would need to upgrade their connection for hydrogen and electricity.
	Hydrogen combustion	The glass sector has recently started investigating the feasibility of using hydrogen to fuel a glass furnace. Until recently the sector did not consider hydrogen to be a viable option due to its flame characteristics, however, there has been renewed interest driven by plans in the EU and UK for large scale production and eventual replacement of natural gas with hydrogen. There are currently five projects in the UK and Europe looking at the feasibility of using 100% hydrogen as well as different proportions of hydrogen blended with natural gas for glass melting. In the UK there has been significant investments into infrastructure and research into hydrogen technologies and it is expected that the first industrial clusters with access to hydrogen supplies could be online as soon as 2026.	Hydrogen is initially planned to be available in a small number of industrial clusters. Initially only a few glass sites which are located close to these clusters will be able to use hydrogen. The production of hydrogen will still require energy in the first instance and without an efficient source of supply, the emission savings across the full glass supply-chain may be diminished.
Remediation to reduce process and combustion emissions	**Carbon capture, utilization and storage**	Carbon capture, utilisation, and storage (CCUS) is the process in which the CO_2 is separated from the flue gas and either used as a feedstock in another process or stored securely underground. Whilst the combustion emissions can be eliminated by fuel switching, the process emissions are more challenging and may require CCUS to meet net zero emissions.	The viability of capturing CO_2 from the furnace waste gas has not been demonstrated. [2] provides an overview of the CCS cluster regions in the UK. Most glass sites are not close to the planned industrial clusters so will not have access to pipelines for transporting the captured CO_2. CCUS is likely to be a very expensive option for reducing process emissions.

A2: Energy Input Calculations

Conversion factors

Delivered energy (MJ) to primary energy (MJ) https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/	
Energy source	**Energy conversion factor**
Natural gas	1.1
Electricity	1.83

WTT fuel sourcing emission factor https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/901692/conversion-factors-2020-methodology.pdf		
Fuel Source	**WTT Emission Factor** ($kgCO_2$-eq/kWh)	**WTT Emission Factor** ($kgCO_2$-eq/MJ)
Natural Gas	-	0.00736
Electricity	0.03217	0.00894
Diesel	-	0.01740

Transportation UK government greenhouse gas reporting 2021 https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021		
Transport method	**kWh / tonne.km**	**$kgCO_2$-eq/tonne**
HGV diesel truck (rigid >17 tonne) average laden	0.86	0.1814

Primary energy

Total embodied energy

$$Total\ embodied\ energy = Primary\ Energy_{Raw\ materials} + Primary\ Energy_{Melting} + Primary\ Energy_{Forming} + Primary\ Energy_{Post-forming}$$

Stage 1: Raw material sourcing

$$Energy_{Raw\ materials} = (1-x).\sum Energy_{PRMSource+Process+Transport} + x.Energy_{CulletSource+Process+Transport}$$

Where x = recycled content

Data sources for embodied energy of primary raw materials & cullet		
	Stage 1: Raw material sourcing	
Literature Source	**Primary raw materials embodied energy** ($MJ/kg_{flat\ glass\ output}$)*	**Cullet embodied energy** ($MJ/kg_{flat\ glass\ output}$)*
[3]	4.052 (0% RC)	-
[4]	4.30 (scaled to 0% RC)	-
[5]	3.83 (4% RC)	
[6]	2.125** (0% RC)	0.18**

* Figures take into account that 1 kg glass produced by 100% raw materials requires 1.192 kg the primary raw material resource input. 1 kg glass produced with 100% cullet requires 1.0 kg the secondary raw material resource input.

**Exclusive of transportation. To calculate energy associated with transporting recover glass, the transportation conversion factors were used, together with the following transportation distances:

- Cullet transportation = 800 km
- Aggregate transportation = 100km

Stage 2 and 3: Glass melting & forming

Recycled content, x from [7]	
Product	**Recycled content, x**
Flat glass	5%
Container glass	45%
Glass wool	55%

Specific energy consumption for raw material melting scaled from [7]					
	Stage 2			Stage 3	
	Energy for combustion at x% RC (MJ/kg)	**Energy for combustion at 0% RC (MJ/kg)***	**Energy for combustion at 100% RC (MJ/kg)****	**Indirect factor = Energy for forming processes as % of $Comb_{x\%RC}$**	**Indirect Energy*****
Flat glass	9.2	9.34	6.54	13.1%	1.39
Container glass	6.4	7.40	5.18	15.5%	1.17
Glass wool	7.5	9.00	6.29	45.0%	6.13

*To scale to 0% RC

$$Combustion\ Energy_{0\%RC} = \frac{Comb_{x\%RC}}{(1-(0.3x))}$$

**To scale to 100% RC

$$Combustion\ Energy_{100\%RC} = 0.7 \times Comb_{0\%RC}$$

***To calculate indirect:

$$Indirect\ Energy = \frac{Indirect\ factor\ \times Comb_{x\%RC}}{(1-Indirect\ factor)}$$

NB: indirect energy consumption is unaffected by recycled content

Primary energy consumption (MJ/kg)						Energy saving with 100% cullet* (MJ/kg)
	Stage 2		Stage 3	Stage 1-3		
	Combustion energy at 0% RC	**Combustion energy at 100% RC**	**Indirect**	**Total at 0% RC**	**Total at 100% RC**	
Flat glass	10.27	7.19	2.54	**16.9**	**12.4**	**4.5 (-26.6%)**
Container glass	8.14	5.70	2.15	**14.3**	**10.5**	**3.8 (-26.8%)**
Glass wool	9.88	6.92	11.23	**25.2**	**20.8**	**4.4 (-17.3%)**

*Accounts for energy required to reprocess cullet

Primary energy consumption compared with literature				
	Recycled content (RC)	**Flat glass**	**Container glass**	**Glass wool**
This study	0%	16.9	14.3	25.2
[3]	0%	18.1	-	-
[8]	0%	19.6	-	-
[5]	4%	15.62	-	-
[9]	23%	-	16.6	-
[10]	Not specified	-	-	20 - 41
[11]	67%	-	-	23.4

Stage 4: Post-forming/Additional processing

	Environmental Product Declaration (EPD) Source	
	Guardian 2021_Ift Rosenheim [4]	**Guardian 2012_iftRosenheim** [3]
Product type	$MJ/kg_{finished\ glass\ product}$	$MJ/kg_{finished\ glass\ product}$
Uncoated flat glass	14.33	18.1
Coating	+ 1.66	n/a
Laminated	+ 8.29	n/a
Toughening	N/A	+ 8.28
	As % of 1 kg flat glass product in EPD	**As % of 1 kg of flat glass product in EPD**
Coating	9.8%	n/a
Laminating	49.2%	n/a
Toughening	n/a	49.1%

Embodied carbon (includes WTT emissions)

Total embodied carbon

$$Total\ embodied\ carbon = GHG\ Emissions_{Raw\ materials} + GHG\ Emissions_{Melting} + GHG\ Emissions_{Post-forming}$$

Stage 1: Raw material sourcing

$$GHG\ Emissions_{Raw\ materials} = (1-x).\sum GHG\ Emissions_{PRMSource+Process+Transport} + x.GHG\ Emissions_{CulletSource+Process+Transport}$$

x = recycled content

Data sources for embodied carbon of primary raw materials & cullet		
Literature source	**Primary raw materials embodied carbon** ($kgCO_2$-eq/ $kg_{flat\ glass\ output}$)*	**Cullet embodied carbon** ($kgCO_2$-eq/ $kg_{flat\ glass\ output}$)*
[3]	0.316 (0% RC)	-
[4]	0.342 (scaled to 0% RC)	-
[5]	0.33 (4% RC)	
[12]	0.208**	-
[13]	-	0.0159**

* Figures take into account that 1 kg glass produced by 100% raw materials requires 1.192 kg the primary raw material resource input. 1 kg glass produced with 100% cullet requires 1.0 kg the secondary raw material resource input.

**Exclusive of transportation. To calculate energy associated with transporting recover glass, the transportation conversion factors were used, together with the following transportation distances:

- Cullet transportation = 800 km
- Aggregate transportation = 100km

Stage 2 and 3: Glass melting & forming

$$Embodied\ carbon_{Melting} = Combustion\ Emissions + Process\ Emissions + \left(Combustion\ Energy\ \times WTT\ Emission\ Factor_{natural\ gas}\right)$$

Recycled content, x from [7]	
Product	**Recycled content, x**
Flat glass	5%
Container glass	45%
Glass wool	55%

Emissions associated with raw material melting scaled from [7]								
	Combustion emissions at x% RC ($kgCO_2$-eq/$kg_{melted\ glass}$)	**Combustion emissions at 0% RC** ($kgCO_2$-eq/ $kg_{melted\ glass}$)*	**Combustion emissions at 100% RC** ($kgCO_2$-eq/ $kg_{melted\ glass}$)**	**Process emissions at x% RC** ($kgCO_2$-eq/ $kg_{melted\ glass}$)	**Process emissions at 0% RC** ($kgCO_2$-eq/ $kg_{melted\ glass}$)	**Process emissions at 100% RC** ($kgCO_2$-eq/ $kg_{melted\ glass}$)	**Indirect factor = Indirect emissions as % of $Comb_{x\%RC}$**	**Indirect emissions** ($kgCO_2$-eq/ $kg_{melted\ glass}$)***
Flat glass	0.55	0.56	0.39	0.19	0	0.192	16.0%	0.158
Container glass	0.38	0.44	0.31	0.11			18.5%	0.125
Glass wool	0.39	0.47	0.33	0.07			54.3%	0.653

*To scale to 0% RC

$$Combustion\ Emissions_{0\%RC} = \frac{Comb_{x\%RC}}{(1-(0.3x))}$$

**To scale to 100% RC

$$Combustion\ Emissions_{100\%RC} = 0.7 \times Comb_{0\%RC}$$

***To calculate indirect

$$Indirect\ Energy = \frac{Indirect\ factor\ \times Comb_{x\%RC}}{(1-Indirect\ factor)}$$

Embodied carbon emissions ($kgCO_2$-$eq/kg_{glass\ output}$)							**Emissions saving with 100% cullet** ($kgCO_2$-$eq/kg_{glass\ output}$)
	Stage 2			**Stage 3**	**Stage 1-3**		
	Combustion emissions (0% RC)	**Combustion emissions (100% RC)**	**Process emissions**	**Indirect emissions**	**Total (0% RC)**	**Total (100% RC)**	
Flat glass	0.63	0.43	0.192	0.16	**0.91**	**0.55**	**0.53 (-41.5%)**
Container glass	0.43	0.31	0.192	0.13	**0.76**	**0.43**	**0.49 (-43.9%)**
Glass wool	0.53	0.37	0.192	0.65	**1.31**	**0.98**	**0.50 (-29.9%)**

	Embodied carbon compared with literature ($kgCO_2$-eq/kg)			
Source	**Recycled content (RC)**	**Flat glass**	**Container glass**	**Glass wool**
This study	0%	1.29	1.13	1.69
[3]	0%	1.068	-	-
[8]	4%	1.37	-	-
[9]	23%	-	1.25	-
[13]	0%	-	1.25	-
[11]	67%	-	-	1.05
[14]	69%	-	-	1.56
[15]	75%	-	-	1.60

Stage 4: Post-forming/Additional processing

Embodied carbon for secondary processing methods from environmental product declarations (EPDs)		
	Guardian 2021_Ift Rosenheim (23% RC)	**Guardian 2012_iftRosenheim (0% RC)**
Product type	**$kgCO_2$-$eq/kg_{glass\ output}$**	**$kgCO_2$-$eq/kg_{glass\ output}$**
Uncoated flat glass	1.086	1.068
Coating	+ 0.268	n/a
Laminated	+ 0.304	n/a
Toughening	n/a	+ 0.392
	As % of 1 kg flat glass product in EPD	**As % of 1 kg of flat glass product in EPD**
Coating	24.7%	n/a
Laminating	27.9%	n/a
Toughening	n/a	36.7%

Additional energy inputs for system

Embodied energy and carbon for glazing fabrication	
Embodied energy ($MJ/kg_{glazed\ unit}$)	**Embodied carbon** ($kgCO_2$-$eq/\ kg_{glazed\ unit}$)*
0.283	**0.0216**

*based on UK electricity grid conversion factor

A3: Calculations for energy balance in each scenario

Total energy input per 1 kg of glass in primary application

$$\boldsymbol{Total\ energy\ input\ (MJ) = PE_{UCFG} + \left(PE_{UCFG} \times \sum YLF\right)}$$

PE_{UCFG} = Primary energy of 1kg uncoated flat glass (MJ)

YLF = Yield loss factor for each processing step

$$YLF_{Process} = Available\ Mass\ \times\ Yield\ Loss_{Process}\ (\%)$$

Yield loss factor and net primary application energy losses (conservative yield)				
	Yield loss factor, YLF	**Energy to process equivalent mass**, MJ	**Energy recovered from yield losses,** MJ	**Primary application net energy losses due to yield losses,** MJ
Uncoated	0.150	2.530	1.070	-1.459
Glazed (Uncoated)	0.035	0.590	0.250	-0.341
Toughened	0.010	0.169	0.071	-0.097
Glazed (Toughened)	0.007	0.118	0.050	-0.068
Laminated	0.045	0.759	0.321	-0.438
Glazed (Laminated)	0.033	0.548	0.232	-0.316
Coated	0.020	0.337	0.143	-0.195
Glazed	0.085	1.425	0.603	-0.822
Glazed (Coated)	0.010	0.169	0.071	-0.097
Total	**30.95%**	**5.219**	**2.208**	**-3.010**

Yield loss factor and net primary application energy losses (aspirational yield)				
	Yield loss factor, YLF	**Energy to process equivalent mass**, MJ	**Energy recovered from yield losses,** MJ	**Primary application net energy losses due to yield losses,** MJ
Uncoated	0.050	0.843	0.357	-0.486
Glazed (Uncoated)	0.018	0.295	0.125	-0.170
Toughened	0.005	0.084	0.036	-0.049
Glazed (Toughened)	0.004	0.059	0.025	-0.034
Laminated	0.023	0.379	0.161	-0.219
Glazed (Laminated)	0.016	0.274	0.116	-0.158
Coated	0.010	0.169	0.071	-0.097
Glazed (Coated)	0.005	0.084	0.036	-0.049
Total	**12.98%**	**2.19**	**0.93**	**-1.260**

Energy input from primary resource per 1 kg of glass in primary application

$$\boldsymbol{Energy\ input\ from\ primary\ resources\ (MJ) =\ Total\ energy\ input -\ (TESP \times RF_{FG})}$$

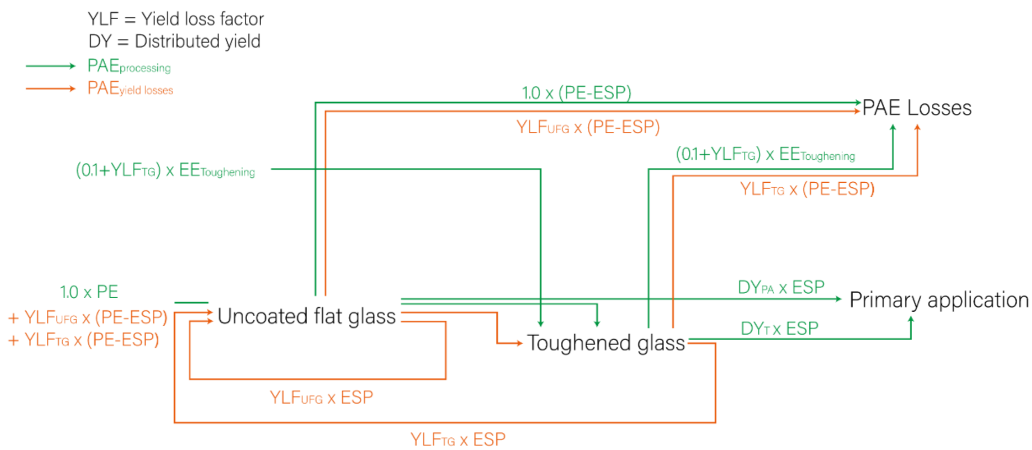
TESP = total energy saving potential from 1 kg of glass output. It is equivalent to the energy saving potential at 100% cullet before any transportation or reprocessing.

$$TESP =\ Total\ embodied\ energy_{0\%\ RC} - (Total\ embodied\ energy_{100\%\ RC} - Raw\ material\ primary\ energy_{cullet})$$

RF_{FG} = Recovered factor for uncoated flat glass from 1 kg of collected product

Primary application energy (PAE) losses

$$\boldsymbol{PAE\ Losses = PAE\ Losses_{processing} + PAE\ Losses_{yield\ losses}}$$



PAE Losses from processing steps

$$\boldsymbol{PAE\ Losses_{processing} = Processing\ energy_{Uncoated\ glass} + \sum Processing\ energy_p}$$

Uncoated glass

$$Processing\ energy_{Uncoated\ flat\ glass}\left(\frac{MJ}{kg}\right) = Total\ embodied\ energy_{0\%\ RC}\left(\frac{MJ}{kg}\right) - TESP\left(\frac{MJ}{kg}\right)$$

Primary processing methods

$$Processing\ energy_p = \left(Distributed\ yield_p, kg + \sum YLF_{process}\right) \times Embodied\ energy_p$$

Where *p*, is a processing step e.g. coating, laminating, toughening or glazing fabrication

e.g. for toughened glass in conservative yield

$$Processing\ energy_{Toughened} = (0.1 + 0.010 + 0.007) \times Embodied\ energy_{toughening\ process}$$

e.g. for glazed in conservative yield

$$Processing\ energy_{Glazed} = (0.845 + 0.035 + 0.007 + 0.033 + 0.010) \times Embodied\ energy_{glazing\ fabrication}$$

PAE Losses from yield losses

$$\boldsymbol{PAE\ Losses_{yield\ losses} = (PE_{UCFG} - TESP) \times \sum YLF}$$

Total energy available for recovery (recoverable energy) from 1 kg of glass product in primary application

The total energy available for recovery is evaluated as the energy saving potential (ESP) before reprocessing (see above).

Recovered energy

$$\boldsymbol{Recovered\ energy_{SA} = Collected\ Factor_{SA} \times NESP_{UCFG}}$$

Where NESP = Energy saving potential after reprocessing

$$NESP_{UCFG} = Total\ embodied\ energy\ at\ 0\%\ RC_{UCFG} - Total\ embodied\ energy\ at\ 100\%\ RC_{UCFG}$$

Distribution of 1 kg of glass product in primary application to secondary application					
	Collected factor				
Scenario	Flat	Container	Wool	Aggregate	Landfill
1	0.00	0.10	0.01	0.74	0.15
2	0.30	0.30	0.30	0.10	0
3	0.90	0	0	0.10	0

Unrecovered energy

$$\boldsymbol{Unrecovered\ energy_{SA} = Recoverable\ energy_{UFG} - Recovered\ energy_{SA}}$$

Secondary application energy (SAE) losses

$$SAE\ Losses = \sum (Collected\ Factor_{SA} \times Processing\ energy_{SA})$$

$$Processing\ energy_{SA}\ = Total\ embodied\ energy\ at\ 0\%\ RC_{SA} - ESP\ before\ reprocessing_{SA}$$

A4: Total tonnage and CO_2 emissions for each glass sub-sector

Sector emissions

	Total tonnage to market (kt)	*% Recycled Content from Pre-consumer*	*% Recycled Content from Post-consumer*	*Sector emissions* ($ktCO_2$-e annum)*
Flat glass (conservative yield, A)	950	32%	0%	1672
Flat glass (aspirational yield, B)	950	32%	0%	1552
Container glass	2700	10%	55%	2435
Glass wool	288	31%	24%	543
Other glass products	395	10%	0	475

Flat glass

$$Sector\ emissions \left(\frac{kgCO_2}{annum}\right) = Mass\ to\ market\ \left(\frac{kg}{annum}\right) \times Emissions\ per\ unit_{Scenario\ 1A}\left(\frac{kgCO_2}{kg}\right)$$

Container glass, glass wool & other glass products

$$Sector\ emissions\ = \left((1-x)Embodied\ carbon_{x=0\%} + x.Embodied\ carbon_{x=100\%} + z.Embodied\ carbon\ without\ reprocessing_{x=100\%}\right) \times Total\ tonnage\ to\ market$$

x = post-consumer recycled content

z = pre-consumer recycled content

Estimate annual outflow of glass stock (kt/annum)

An outflow of 600 kt and 200 kt of flat glass in 2021 have been taken as a high- and low-end estimate based on annual rates of production in the year 1996 and a 25-year lifetime of a glazing unit and steady growth in the automotive glass market [10], [16], [17].

Emission savings ($ktCO_2$-eq/annum)

$$Emission\ savings\ per\ annum\ (\text{kgCO2e/annum}) = Net\ recovered\ emissions\ per\ kg\ of\ collected\ flat\ glass_{Scenario\ X}(\text{kgCO2e}) \times Estimate\ annual\ outflow(kg)$$

Emissions reduction potential

	Conservative Yield				***Aspirational Yield***					
	Scenario 1A		***Scenario 2A***		***Scenario 1B***		***Scenario 2B***		***Scenario 3B***	
Estimate annual outflow (kt)	200	600	200	600	200	600	200	600	200	600
Emissions savings (ktCO2e/annum)	18.5	55.6	92.1	276.3	18.5	55.6	92.1	276.3	96.2	288.6
Emissions savings as % of glass sector total (with reference to conservative yield FG baseline)	0.36%	1.09%	1.80%	5.39%	0.36%	1.09%	1.80%	5.39%	1.88%	5.63%
Emissions savings as % of glass sector total (with reference to aspirational yield FG baseline)	0.37%	1.11%	1.84%	5.52%	0.37%	1.11%	1.84%	5.52%	1.92%	5.77%
Emissions savings as % of flat glass sector total (with reference to aspirational yield FG baseline)	1.11%	3.33%	5.51%	16.52%	1.11%	3.33%	5.51%	16.52%	5.75%	17.26%

	Conservative Yield				***Aspirational Yield***					
	Scenario 1A		***Scenario 2A***		***Scenario 1B***		***Scenario 2B***		***Scenario 3B***	
Emissions savings as % of flat glass sector total	1.19%	3.58%	5.93%	17.80%	1.19%	3.58%	5.93%	17.80%	6.20%	18.59%
Glass sector emissions (ktCO2e/annum) - conservative yield in FG production	5125	5125	5125	5125	5125	5125	5125	5125	5125	5125
Glass sector emissions (ktCO2e/annum) - aspirational yield in FG production	5005	5005	5005	5005	5005	5005	5005	5005	5005	5005
Flat glass sector emissions (conservative yield)	1672	1672	1672	1672	1672	1672	1672	1672	1672	1672
Flat glass sector emissions (aspirational yield)	1552	1552	1552	1552	1552	1552	1552	1552	1552	1552

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