Supply Chain Energy and Greenhouse Gas Analysis Using the Materials Flows through Industry (MFI) Tool: Examination of Decarbonization Technology Scenarios for the U.S. Glass Manufacturing Sector

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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List of Acronyms

CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
EIA	Energy Information Administration
GHG	Greenhouse Gas
GJ	Gigajoule
H2	Hydrogen
MFI	Material Flows through Industry
NREL	National Renewable Energy Laboratory
PM	Practical Minimum
R&D	Research and Development
RE	Renewable Electricity
ReEDS	Regional Energy Deployment System
SMR	Steam Methane Reforming
SOTA	State-of-the-Art

Executive Summary

Glass manufacturing is a major sector of the U.S. economy, and glass products in multiple subsectors—flat glass, container glass, and fiberglass—are a part of everyday life. Despite glass manufacturing's long history, there are still many opportunities for glass production to improve in terms of both overall energy consumption and greenhouse gas (GHG) emissions reductions. Using the National Renewable Energy Laboratory's Material Flows through Industry tool, multiple scenarios are examined for each glass sub-sector by applying a combination of energy reduction, increased electrification, hydrogen cofiring, a more renewable electric grid, and increased use of cullet. Scenario results for the flat glass, container glass, and fiberglass sub-sectors show the effect that each technology change has on total energy demand and GHG emissions, relative to an industry baseline that reflects current manufacturing practices. Total energy demand can be reduced by 75%-83% compared to baseline inputs, depending on the sub-sector, and GHG emissions are reduced by 82%-86%. Applying the maximum level of improvements listed here has the potential to save over 305 million GJ and 27 million metric tons of GHGs by 2050. Additional decarbonization options are possible for glass but are left for later analysis due to cost, feasibility, or data issues.

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1 Introduction

Glass production is a major industry with a history dating back thousands of years and products that are used frequently in everyday life. Glass has a high energy intensity due to the temperatures required to form the glass melt and generate products with uniform properties. The stages for glass production follow the same order of operation despite having differing material specifications, beginning with batch formation of raw materials, followed by melting and homogenization of batch materials, refining, forming, and post-processing (Cresko et al. 2022). Despite the high energy intensity, energy demand for glass production was only 0.8% of the U.S. total energy demand for 2018, as glass has lower production volumes than other commodities such as cement, metals, or pulp and paper (U.S. EIA 2018).

The glass manufacturing energy bandwidth report (DOE (U.S. Department of Energy) 2017), published by the U.S. Department of Energy in 2017, provides an overview of the options available for energy reduction and shifts in technology within U.S. glass manufacturing. In that report, energy consumption levels are estimated for subsets of the glass industry based on data from the literature combined with results from the U.S. Energy Information Administration's Manufacturing Energy Consumption Survey. Alternate ingredients for glass are not considered in this report or other studies of glass decarbonization due to the effect this would have on product quality, cost, reliability, and other requirements of the glass industry (alternate materials defined here as alternate raw materials, excluding recycled content from this definition). Heat recovery and efficiency improvements are the focus of the glass bandwidth report, which examined "bands" of energy consumption in four broad levels. The energy bands were developed for the major glass sub-sectors of container, flat, fiber (including wool), and specialty glass, which encompasses other glass products not included in one of the main sub-sectors listed here. These energy bands include:

- *Baseline*, which represents the current state of technology, is the energy consumption in 2010, determined through industry and academic reporting of glass production for each glass product.
- *State of the art* (SOTA) is the energy consumption that may be possible by adopting existing best technologies and practices available worldwide. These energy levels, like baseline energy levels, are specific to each glass sub-sector.
- *Practical minimum* (PM) is the energy consumption level that may be possible if applied research and development (R&D) technologies under development worldwide are deployed simultaneously.
- *Thermodynamic minimum* (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications. The thermodynamic minimum energy level is not considered in this case study due to its lack of feasibility in commercial settings.

In addition to the glass bandwidth report, several recent studies have looked at methods to decarbonize the glass industry (Zier et al. 2021; Furszyfer Del Rio et al. 2022), with a focus on broad categories such as heat recovery, energy reduction through efficiency improvements, changes in the method of operation, and fuel substitution. Earlier reports focused on the potential for greenhouse gas (GHG) or energy reduction (Vallack et al. 2011; Worrell et al. 2008; British Glass 2017) and looked at the effects that individual steps would have on the current footprint of the glass industry. Reports on the effects that recycled glass (cullet) has on the glass production process, including energy and GHG reduction, are also well-known (Zulkarnain et al. 2021). Cullet serves to reduce both the virgin raw material inputs and energy inputs to the furnace, the latter due to removing the heat input requirement for initial glass formation reactions to occur. What is absent from the literature on glass production is an exploration of what implementing the previously listed strategies, including reduction of energy inputs, cullet addition, or added electrical furnace melting, would look like for and supply-chain energy reduction and GHG emissions. Previous studies, such as the glass bandwidth report, have addressed the effects of reducing direct energy consumption at each stage of the manufacturing process, and this report expands on that work to address energy consumption within the supply chain as well as the effects from fuel switching, changes to the electric grid, and a different method of furnace operation.

Pilot-scale programs exist to showcase the feasibility of the available options, and individual companies can implement improvements to a single production line (Lecompte et al. 2017; Springer and Hasanbeigi 2017). However, the results of such programs are limited to smaller-scale efforts and still require development to reach industrial volumes and quality. A literature review reveals that there is an opportunity to combine the effects of energy efficiency and alternative fuel use, explore their synergies, and identify which combination would provide the greatest reductions in both energy demand and GHG emissions. The analysis reported here aims to compare the baseline energy requirements and GHG emissions from container glass, flat glass, and fiberglass to several scenarios that would reduce the overall energy input and GHG emissions from the manufacture of these glass products.

2 Methods

The energy consumption and GHG emissions are determined for each glass sub-sector under the baseline and decarbonization scenarios using the Material Flows through Industry (MFI) tool (NREL, n.d.). The MFI modeling tool was developed for performing supply chain analyses of U.S. manufacturing and derived products. It contains a database of industrial products in a recipe form, which tracks the inputs (e.g., raw materials, energy, water) required in the initial manufacturing stages. Recipe inputs use the cut-off approach[1] in determining the inventory. The MFI tool uses a "mine-to-materials" system boundary that begins with natural resource extraction and ends with production at a manufacturing site. The MFI tool applies a bottom-up approach to model the physical units or processes associated with the supply chain of a product. The recipes in the MFI tool are connected to form a linear network that captures the material and energy flows within the U.S. industrial sectors (Hanes and Carpenter 2017), with a default of ten levels included in the supply chain for calculations. The tool allows users to model existing U.S. industrial practices by using the current technology mixes to produce a commodity (the default setting for MFI), or simulate future manufacturing scenarios by varying the technology mixes and/or recipes. Weights are assigned to each process based on the most recently reported industrial production volumes for each product.

The MFI tool uses the network of unit processes across multiple levels of a product's supply chain to calculate the total material and energy inputs required to create the desired product. The output regarding the supply chain energy consumption represents total energy consumption, which is further disaggregated by fuel type. GHG emissions are reported for each type of GHG and are aggregated as CO_2 equivalents using 100-year global warming potential factors. MFI does not consider in-situ GHG process emissions (e.g., CO_2 released stoichiometrically from a chemical reaction); these can be added separately. Co-products are accounted for in MFI using credits for each co-product, and are listed as negative inputs such that their creation represents an avoided production using other methods. Co-products are represented on a mass or energy basis depending on if a physical product or excess energy is created. The outputs from MFI reports include both total and avoided energy and GHG emissions for the selected product.

The recipes in the MFI tool examine effects from a U.S. supply chain perspective only; some processes representing global production are also included, such as for processes used solely or primarily outside the United States. This case study only uses the recipes with U.S.-based weightings because the methods used to manufacture glass do not differ greatly in other regions[2], future projections for electric grid changes only apply to the United States, and the glass bandwidth report uses U.S. energy inputs. Though information is available regarding global supply chain differences for glass and the current electric grid, the glass bandwidth report and the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) model, which is used in this study, each limit their scope to the United States.

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[1] The cut-off approach in LCA creates a system boundary where all impacts from a product end with its recycling or disposal. This is different from other approaches that allocate impacts through recycling or refurbishment on the basis of mass, energy content, economic value, etc. (Nicholson et al. 2009).

[2] One of the main exceptions to this statement is the production of soda ash (Na_2CO_3), which is a major input for soda-lime glass production. The United States uses primarily natural trona ore as a source for soda ash, from a large deposit in Green River, Wyoming, while other countries rely on one of two synthetic methods for production.

2.1 Scenario Development

The glass products examined here are flat glass, container glass, and fiberglass, which together represented 81% of U.S. glass production in 2010 (DOE (U.S. Department of Energy) 2017). Note that in this report, fiberglass refers to the glass fiber itself and not the composite material that can also be referred to as fiberglass. Specialty glass has multiple subcategories that are not produced at the same volume as the other glass types (DOE (U.S. Department of Energy) 2017) and these may not follow the same recipe or method of production within the sub-sector. Container glass is the largest individual sub-sector. However, flat glass (the second-largest sub-sector) and fiberglass both have large growth potentials due to their inclusion in solar and wind technologies (respectively) that are projected to experience widespread deployment in long-term planning studies. Initial energy requirements for each product recipe are taken from the Baseline energy levels as listed in the glass bandwidth report, and material inputs remain equal to the recipes for each glass type in the MFI tool. Material inputs for the fiberglass recipe are sourced from the U.S. Life Cycle Inventory database (NREL 2012). The flat glass recipe comes from ecoinvent (Wernet et al. 2016), and the source for the container glass recipe is a life cycle assessment study of a glass bottle (Uthayakumar 2020).

Glass recipes in the MFI tool are designed with 100% virgin material inputs, according to the input data for each recipe, so adjustments are made for each glass sub-sector and scenario to account for the effect that cullet would have on material and energy inputs. Adjustments here refer to reducing virgin material inputs when cullet is used and reducing furnace energy requirements by 2.5% for each 10% addition of cullet in all recipes (Westbroek et al. 2021). Cullet as a raw material is added through the cutoff approach for reuse, where all burdens remain with the first lifetime of the material and the additional inputs required are the material or energy requirements for cleaning, processing, and transporting the cullet for reuse.

Several electric grid scenarios have been developed using the ReEDS model, which examines the current and possible future expansion of the U.S. electrical power sector (NREL, n.d.). The grid mixes explored in this case study are the current electric sector (based on the ReEDS representation of generation technologies in use in 2022) and projections for the generation mix in 2030 and 2050 assuming technological advancements and policy changes that approximate those of the Biden administration's goals for net-zero grid emissions by 2035. These generation mix results from ReEDS assume a lowered cost for renewable electricity generation (low RE cost) and policy drivers that achieve 95% emissions reduction compared to 2005 by 2035, and net zero emissions by 2050 (95% by 2035)[3]. Projections of the electric grid mix in 2030 and 2050 using these assumptions are referred to in this report as ReEDS 2030 and ReEDS 2050, respectively. There are a range of possible generation mixes from ReEDS solutions for years between 2030 and 2050; however, only two potential future grid mixes are selected for comparison in this study, as changes to the electric grid are only one of several possible technologies considered.

The same set of scenarios is applied to each glass type, each of which has a different energy level and set of improvements depending on the options listed in the glass bandwidth report. A glass container production line moving from baseline to state-of-the-art energy levels would not have

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[3] ReEDS scenarios do not follow administration goals, so the selected scenario for this analysis is the closest to the stated Biden administration policy.

the same absolute or relative change compared to flat glass or fiberglass, since different inputs count as state-of-the-art for the sub-sectors. The same applies to the PM energy levels for each glass sub-sector. Table 1 lists the scenarios in this case study for flat, container, and fiberglass.

Table 1. Scenarios Considered in MFI for Each Glass Sub-Sector

SMR refers to current hydrogen production from steam methane reforming, while RE refers to hydrogen produced via electrolysis and renewable electricity. 2030 and 2050 grid mixes are based on the "95% by 2035" ReEDS scenario.

Scenario	Scenario Name	Grid Mix	Electric Input (%)	Cullet Use (%)	Technologies (see Table 2)	Hydrogen Technology
1	Baseline	2022	Baseline	0	Current	0
2	SOTA	2022	Baseline	0	SOTA	0
3	PM	2022	Baseline	0	PM	0
4	SOTA H_2	2022	Baseline	0	SOTA	20%, SMR
5	SOTA 2030	2030	Baseline	0	SOTA	0
6	SOTA 2030 hybrid	2030	50	0	SOTA	0
7	SOTA 2030 H_2	2030	Baseline	0	SOTA	20%, RE
8	SOTA 2030 hybrid H_2	2030	50	0	SOTA	20%, RE
9	SOTA 2050 hybrid H_2	2050	50	0	SOTA	20%, RE
10	PM 2050 hybrid H_2	2050	50	0	PM	20%, RE
11–20	Repeat 1–10	—	—	30	—	—
21–23	Repeat 8–10	—	—	90	—	—

We consider 23 scenarios and focus on cullet levels of 0%-30%, as these rates are more reflective of current U.S. glass manufacturing (as compared to higher levels of external cullet use). The 90% cullet scenarios are used to demonstrate the total reductions that are possible when technological improvements and electric grid changes are combined with the highest feasible cullet levels. We select 90% as the maximum cullet, as some level of virgin inputs would still be required to control the material properties and color of the final product, even with closed-loop cullet sourcing and processing. This maximum level of cullet use would require closely-monitored closed-loop recycling systems to ensure that each manufacturing facility receives cullet with a composition near to that of the new product. If cullet grades are mixed and incoming cullet composition has a high variance, this affects the quality and purity of the new glass product and may cause new products to not meet the industry specifications. The 90% rate is also the collection rate goal for glass containers in Europe, which is currently at 79% (FEVE 2022).

2.2 Technology Descriptions

The technologies listed in Table 2 are included in either the SOTA or PM energy levels from the glass bandwidth report.

Table 2. Technologies Applied to State-of-the-Art or Practical Minimum Energy Reductions for Each Sub-Sector and Stage of U.S.-Based Glass Production

Any technology marked with an "X" indicates it is included in the energy level listed in the column heading, with energy reductions combined as a reduction in natural gas or electricity inputs for the listed stage of production.

Technology	Stage	SOTA	PM	Products
Motor resizing or variable speed drives	Batching	x	x	All
Improved grinding			x	All
Reduced batch wetting			x	All
Batch and cullet preheating			x	All
Excess furnace air reduction	Melting		x	All
Low-nitrogen oxide burners			x	All
Improved heat transfer/ containment in furnace			x	All
Process heating control systems			x	All, SOTA fiber
Submerged combustion			x	All
Forehearth process control	Forming	x	x	All
Forming compressor control		x	x	Container
Forehearth energy efficiency			x	All
Improved fiber drying	Finishing		x	Fiber
Autoclave radio laminating			x	Flat
Annealing optimization		x	x	Flat, container
More-efficient tempering			x	Flat

According to the glass bandwidth report, the technology improvements with the largest opportunity for energy savings in all glass sub-sectors are improved heat transfer and containment, minimizing excess air for combustion (which is also improved with electric furnaces), and batch or cullet preheating. Two of these improvements focus on energy efficiency and minimization of losses, which also provides an economic incentive for manufacturers, and preheating already exists in limited capacities (Karellas et al. 2018). Preheating exists for cullet systems and case studies are being developed for batch systems. The most significant improvements that apply to specific glass sub-sectors are tempering with a higher heat transfer rate for flat glass; improving and adjusting the annealing process for container glass; and improved fiber drying technology for fiberglass. Details about the savings from each improvement can be found in the appendix with a more detailed description in Table A-4 of the glass bandwidth report (DOE (U.S. Department of Energy) 2017).

The addition of cullet not only reduces energy requirements for melting, but also reduces virgin material inputs that produce carbon dioxide (CO_2) through decomposition at higher temperatures. Reducing soda ash and limestone, the second- and third-largest components of soda-lime glass after silicon dioxide, avoids the CO_2 emissions inherent to the chemistry of these ingredients. The decomposition CO_2 emissions are process emissions that are not accounted for in the MFI tool; decomposition emissions in this analysis are calculated manually based on the chemical makeup of the input materials. At high temperatures in a glass furnace, materials containing a carbonate (such as $CaCO_3$ in limestone) can decompose to form the metal oxide (CaO) and CO_2. Material decomposition for soda-lime glass typically means that under normal circumstances, 1.16-1.17 tons of raw material are required to produce 1.0 ton of glass product to account for the material losses from CO_2 decomposition. Hence, having less raw material that decomposes and creates CO_2 process emissions would lower the overall GHG emissions for that scenario. SOTA and PM goal energy levels are each defined in the glass bandwidth report for each glass type (DOE (U.S. Department of Energy) 2017), including the fuel mix for those sub-sectors.

Current hydrogen production technologies are primarily sourced from steam methane reforming (SMR) processes, with only a small percentage of hydrogen generated through electrolysis with renewably-sourced electricity (Bermudez, Evangelopoulou, and Pavan 2022). Hydrogen blend rates are being studied for many applications to determine the maximum amount of hydrogen that can be added without creating issues such as hydrogen embrittlement of steel, increased leak rates (Melaina, Antonia, and Penev 2013), or requiring redesign of existing infrastructure to account for differences in the behavior of hydrogen and natural gas (Ma et al. 2009; Energy Networks Association 2021). We select one of the higher-end estimates of 20% (v/v%) from the previous sources to represent a goal for hydrogen blending with the existing natural gas supply. Hydrogen blending is set at either 0% (no blending) or 20% in each scenario. In scenario 4, 20% hydrogen is added to SOTA energy levels to account for the possibility that this change could be made in the near term, which is a feasible time frame for when SOTA energy levels could be applied to existing furnaces. Hydrogen has a higher firing velocity, longer flame length, decreased volumetric energy content, and produces different flue gases when combusted compared to natural gas, which are all factors that must be accounted for when hydrogen is added in a glass furnace. The scenario also uses current production methods that are primarily SMR of natural gas. In scenarios 7–10, 20% hydrogen produced via electrolysis and renewable electricity is applied as a blend of the natural gas supply (see Table 1).

Many options in the glass bandwidth report and other decarbonization studies focus on heat recovery and energy efficiency, where natural gas continues to be used as the primary fuel for combustion. Natural gas produces GHG emissions even at peak melting efficiency due to their reaction chemistry, which is one of the main sources of GHGs from glass production. Electric furnace melting can remove significant amounts of CO_2 from the flue gas stream of a glass furnace by reducing fossil fuel combustion. Electric melting has been demonstrated in multiple locations and can take advantage of low-carbon electricity generation methods (Meuleman 2017; Biennek, Jodeit, and Linz 2009). Some disadvantages to electric melting still exist and prevent 100%-electric furnaces from being used at this time (Krijgsman and Marsidi 2019), which is why the largest contribution from electricity is kept at 50% of total melting energy input. Designs for 100% electric melting are on the smaller end of the scale of available furnace sizes for specialty or container glass, and are not yet designed for the size range of flat glass furnaces (Reynolds 2019). In addition to a current higher operating cost due to a difference in fuel costs and a lack of real-world data from which to draw, a significant furnace redesign would be required for flat glass production that operates at a much larger furnace size than other sub-sectors. A hybrid option takes advantage of the input from renewable electricity with a larger number of electrodes placed throughout the furnace to provide the resistive heating that replaces natural gas combustion. Hybrid furnaces have an energy input range of 20%-80% natural gas (Morris 2020; “Hybrid Furnaces - Flexible Energy Mix,” n.d.), which demonstrates the change from moving towards a 100% electric furnace while retaining the flame control used in traditional glass furnaces. Assuming 50% of furnace energy input from electricity acts as a midpoint of the stated range for these hybrid furnaces. Scenarios that include the “hybrid” descriptor in their name refer to the 50% electric melting inputs described here.

ReEDS deployment projections are applied to glass production scenarios to illustrate the effect that decarbonizing the electricity generation mix has on the overall energy requirements and GHG profile for glass production. ReEDS grid mixes are selected for each scenario based on the energy efficiency improvements and technology changes that are consistent with the year of the grid mix. Near-term technology changes are initially applied to the 2030 grid mix, in single stages followed by scenarios that combine several alterations from earlier scenarios. Scenarios that include all technology changes applied together requires a more substantial shift within the glass industry and assumed to be longer term developments (i.e., 2050 and the 2050 grid mix).

3 Results

In this section, the MFI results for GHG emissions and energy consumption are grouped by glass product type. All energy levels and GHG emissions are shown for a glass sub-sector at once, including all cullet levels, so that the effect of cullet can be compared to technology improvements at differing recycle rates.

3.1 Energy Level and GHG Emission Scenario Results

Figures 1 and 2 show the total supply chain energy demand and GHG emissions, respectively, for the flat glass sub-sector when evaluating each of the baseline and alternate scenarios in MFI. Results are shown based on their contribution to the total, with energy demand including contributions from process fuels (heating), feedstock (materials), electricity, and transportation. GHG emissions are separated into Scope 1, 2, and 3 emissions. Scope 1 includes direct manufacturing emissions of CO_2 that are from either process fuels or material decomposition; Scope 2 includes emissions from purchased electricity; and Scope 3 emissions include upstream inputs from the glass supply chain. Total energy demand and GHG emissions for container glass are shown in Figures 3 and 4, respectively, while the same metrics for are shown for fiberglass in Figures 5 and 6.

When the energy source is altered in scenarios that involve SOTA or PM energy levels, the total energy input remains the same to match the values from the glass bandwidth report and ensure that the energy source is the only variable affected. This is demonstrated when a hybrid melter is used, which affects the electricity inputs, or when hydrogen supplements natural gas. All scenarios involving hydrogen (including fossil fuel-based or renewable energy-based) replace 20% of the natural gas volume that would normally be present for that scenario's stated level of furnace energy input.

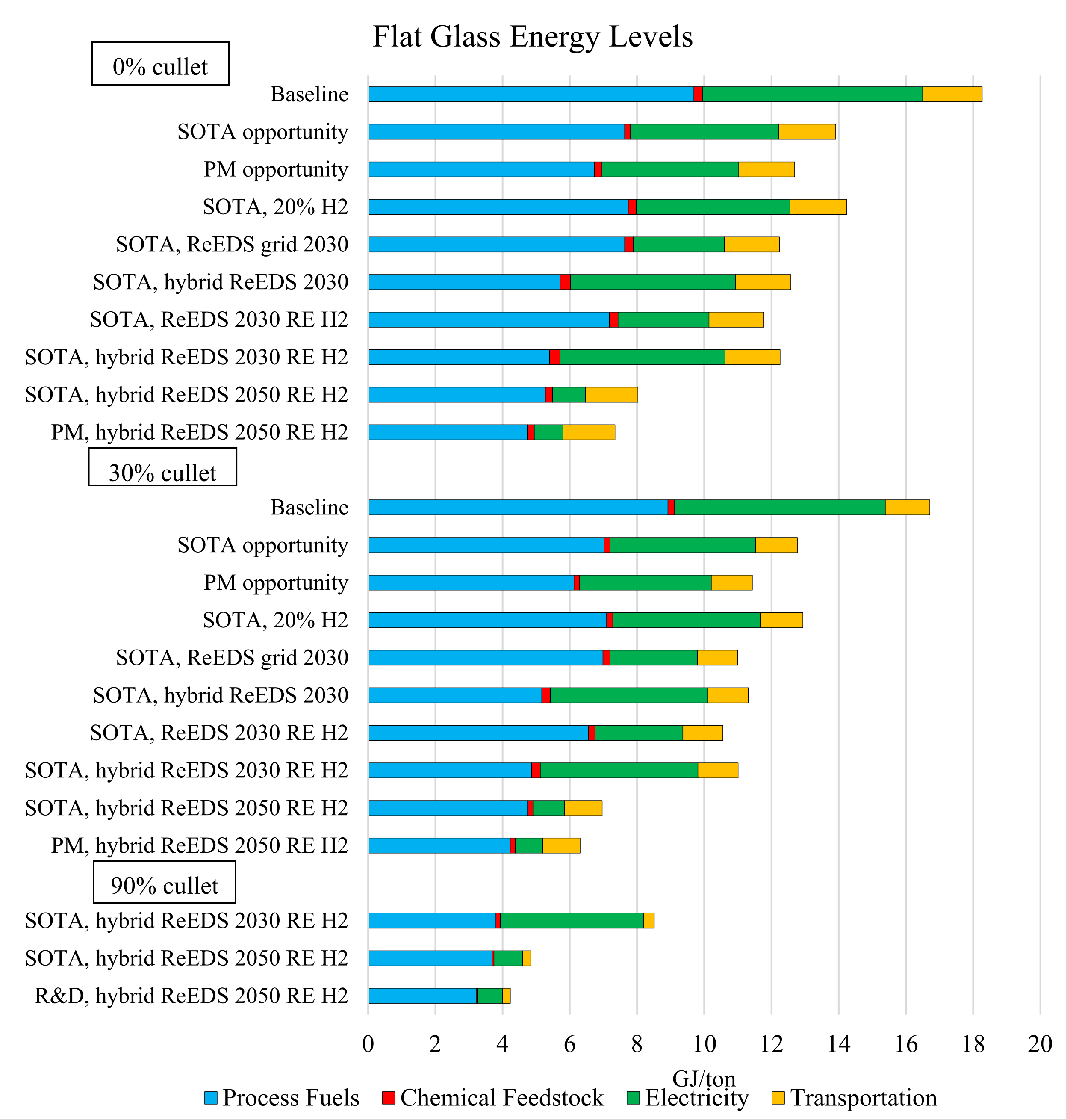

Figure 1. Total energy demand for flat glass manufacturing scenarios, based on output from the MFI tool

2030 and 2050 grid mixes are based on the “95% by 2035” ReEDS deployment projection

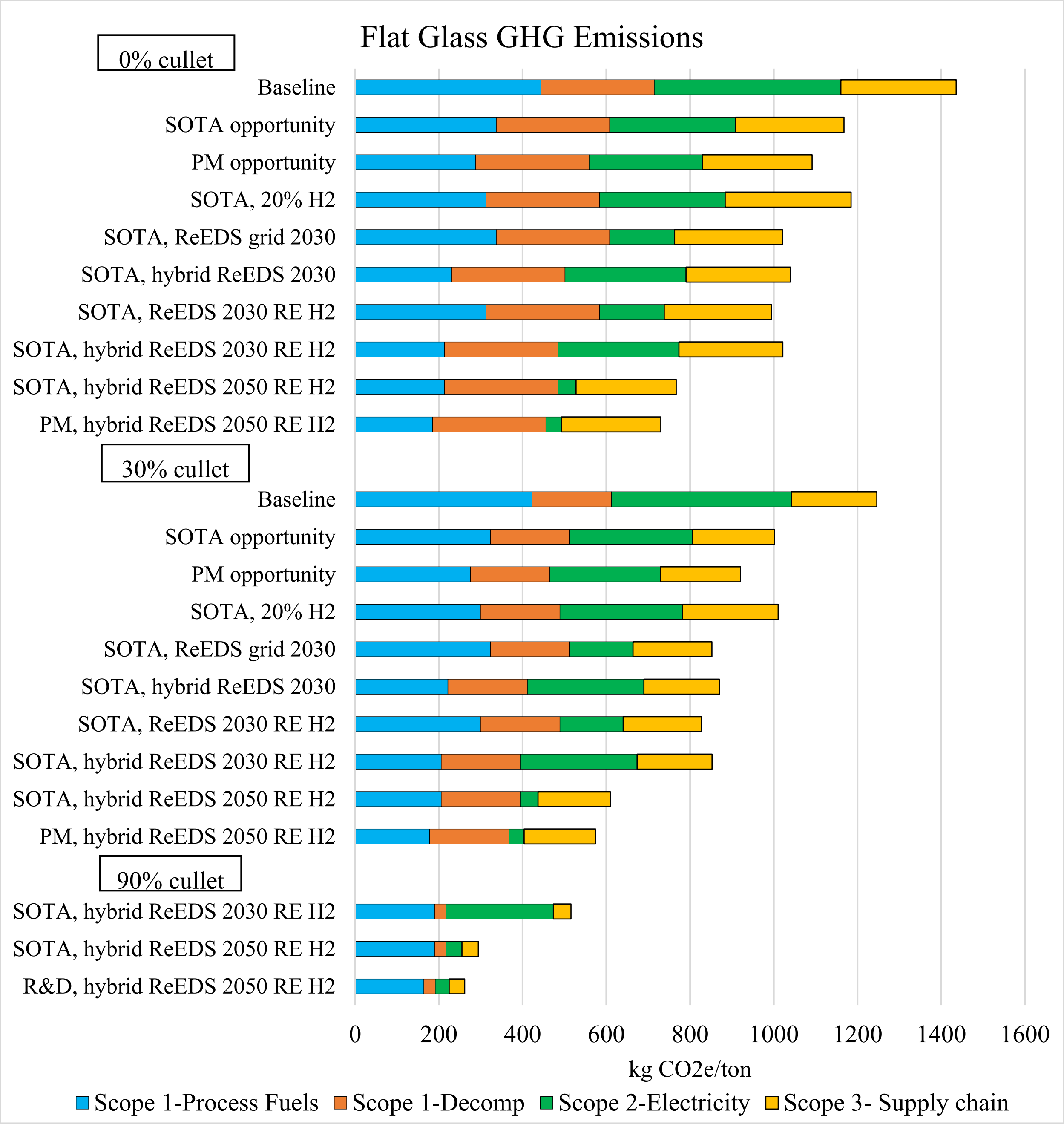

Figure 2. Greenhouse gas emissions for flat glass manufacturing scenarios, based on output from the MFI tool

2030 and 2050 grid mixes are based on the “95% by 2035” ReEDS deployment projection

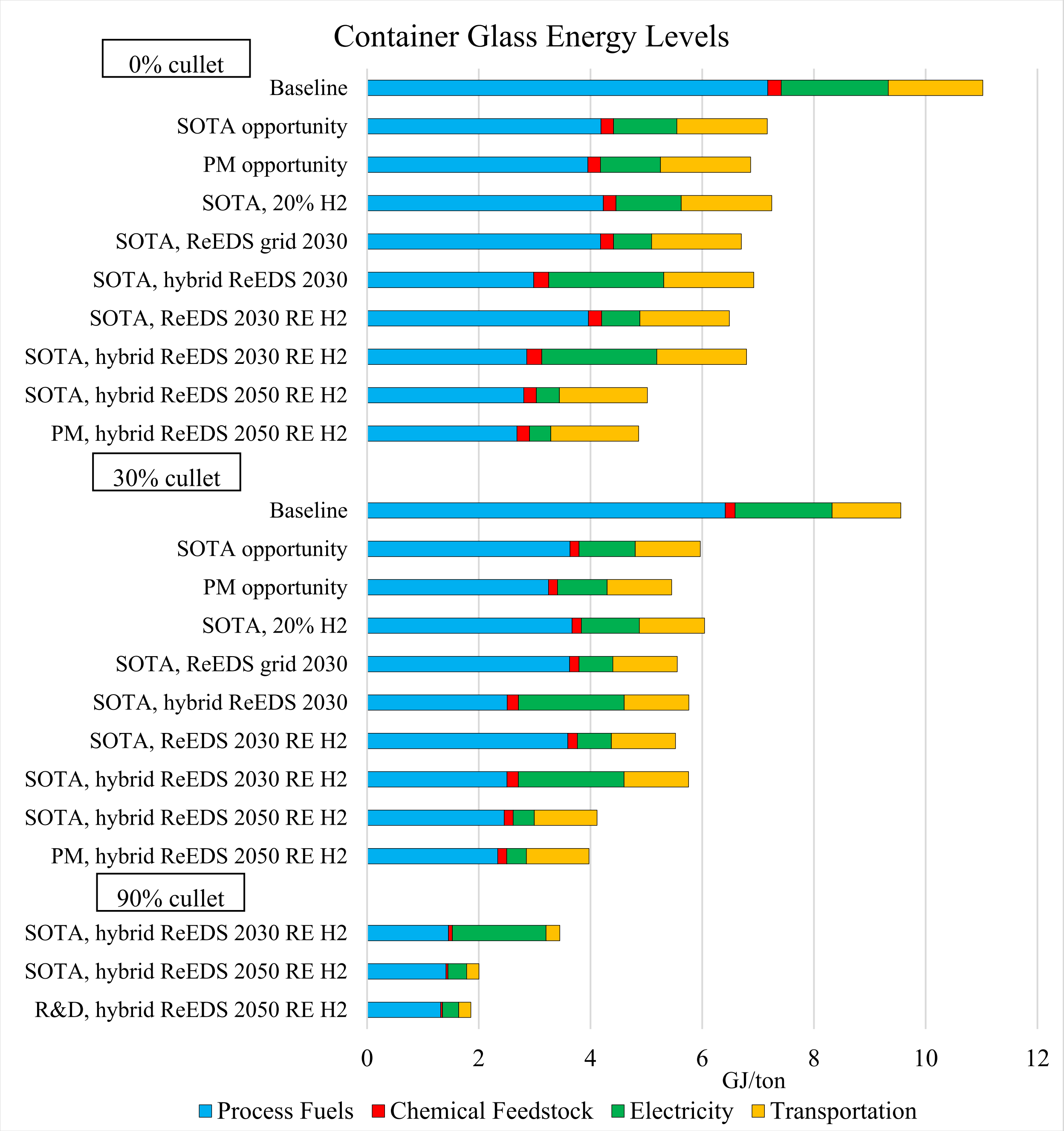

Figure 3. Total energy demand for container glass manufacturing scenarios, based on output from the MFI tool

2030 and 2050 grid mixes are based on the "95% by 2035" ReEDS deployment projection

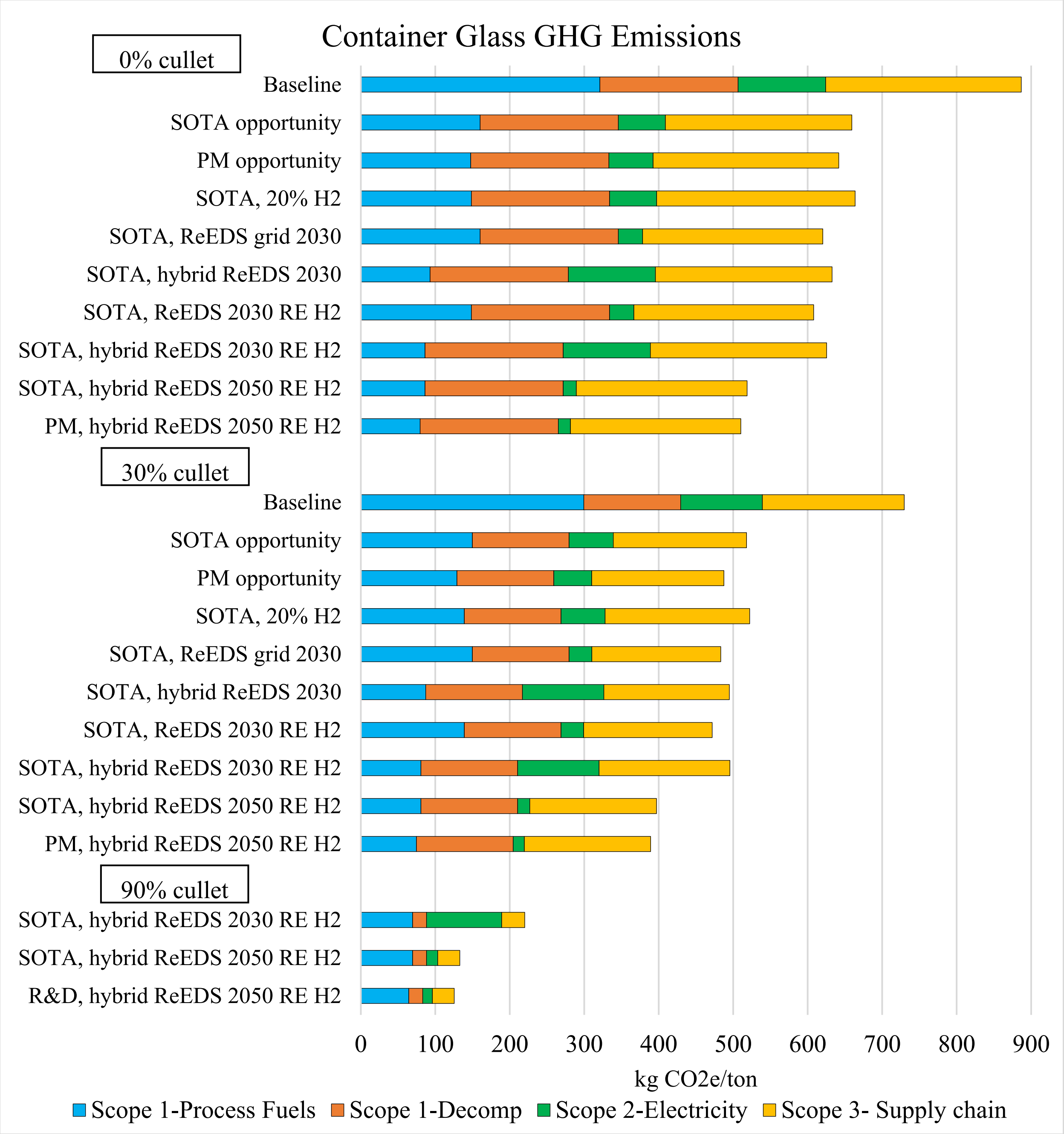

Figure 4. Greenhouse gas emissions for container glass manufacturing scenarios, based on output from the MFI tool

2030 and 2050 grid mixes are based on the “95% by 2035” ReEDS deployment projection

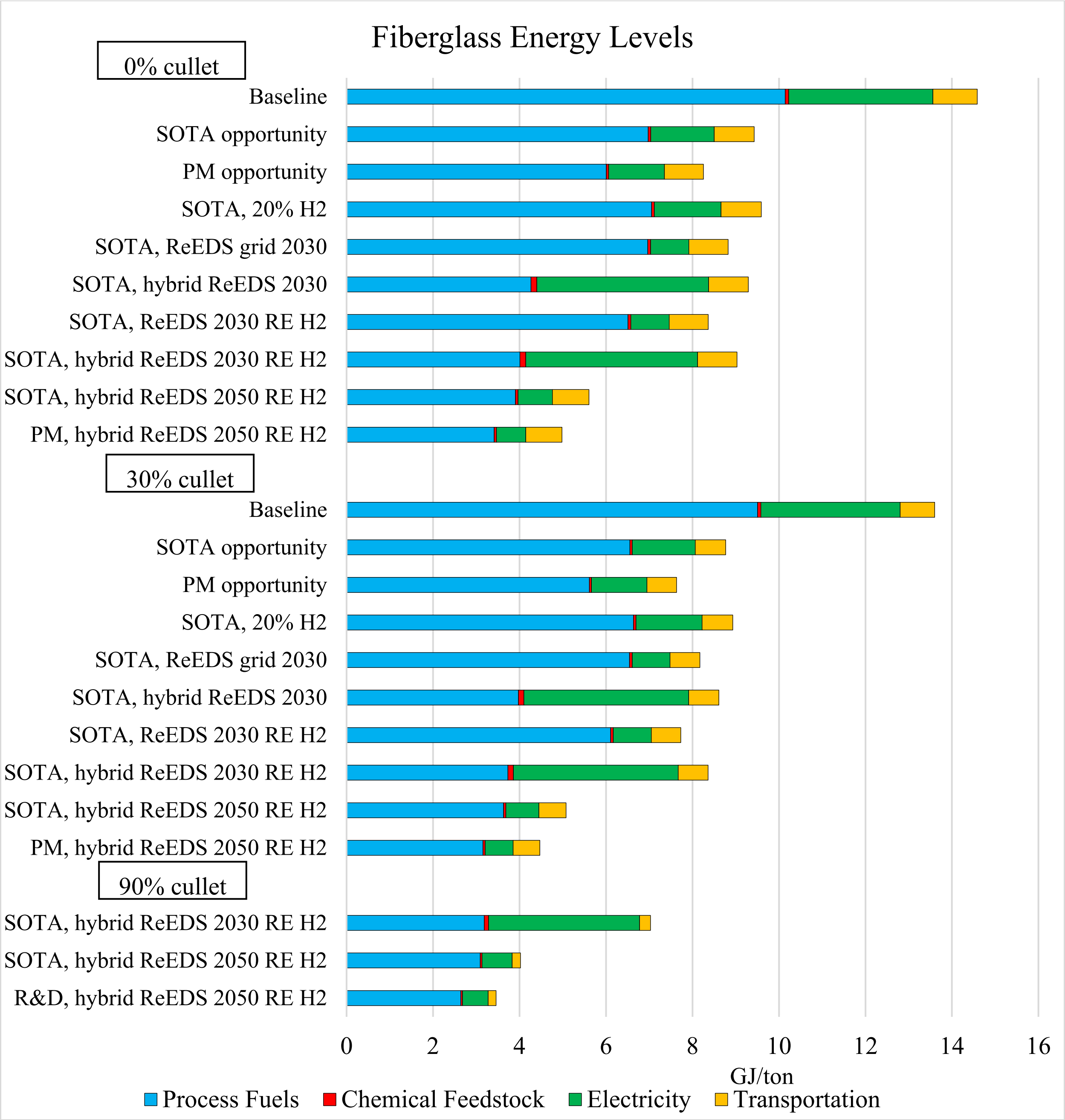

Figure 5. Total energy demand for fiberglass manufacturing scenarios, based on output from the MFI tool

2030 and 2050 grid mixes are based on the "95% by 2035" ReEDS deployment projection

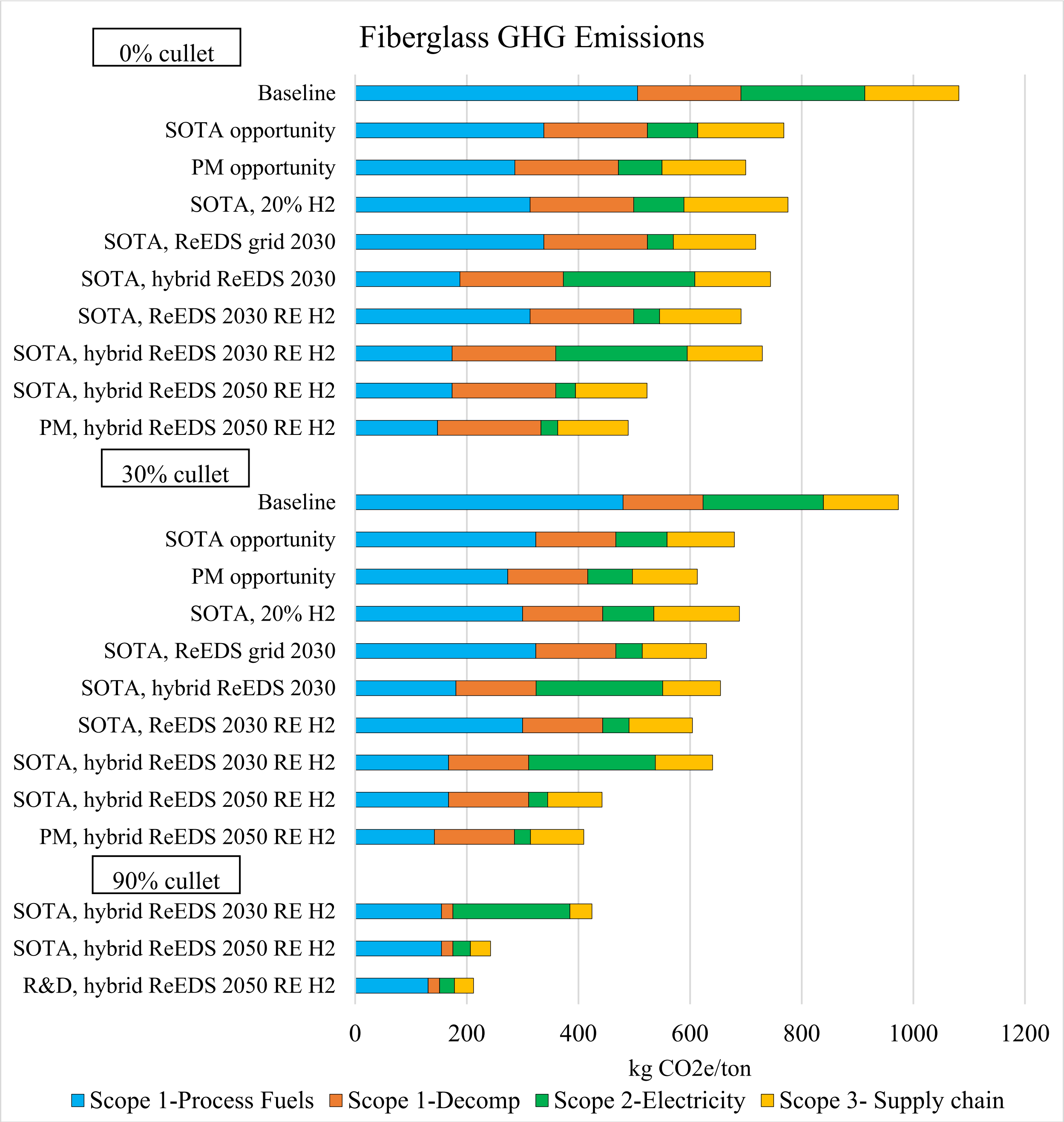

Figure 6. Greenhouse gas emissions for fiberglass manufacturing scenarios, based on output from the MFI tool

2030 and 2050 grid mixes are based on the “95% by 2035” ReEDS deployment projection

The effect of CO_2 emissions from material decomposition decreases linearly as cullet levels increase, as these are solely a result of process emissions and less raw material is required as more cullet is used. In addition to having lower raw material requirements, cullet also has a compounding energy reduction effect as a result of the 2.5% furnace energy savings for each 10% of cullet that is used. Cullet can be used at any level in a furnace because glass does not exhibit a loss in properties upon melting and reuse for new products. It is the result of sorting and cleaning from contamination that determines the cullet level accepted by manufacturers. The trends for energy level and GHG emissions for each set of scenarios remain fairly consistent when cullet level is kept constant. In other words, improvements applied to flat glass with 0% cullet have close to the same effect as those same changes applied to flat glass with 30% cullet.

Energy and GHG emissions from transportation remain fairly consistent for the same cullet level. The main changes across scenarios are from different levels of energy inputs and energy sources, which have less effect on transportation than material inputs that are reduced when cullet is added. Also, when 50% electricity inputs are selected (hybrid melting), energy and GHG emissions from process fuels decrease but are partially offset by an increase in energy and GHG emissions from electricity use. The energy demand from these scenarios would not be useful in a direct comparison to energy inputs for glass production, which do not account for total energy use or additional supply chain energy.

Energy and GHG emissions from the supply chain range from 8-45% of the total. This is a significant contribution to GHG emissions for several scenarios, especially when cullet use is low. The supply chain represents a larger fraction of total energy demand and GHG emissions when there is a higher proportion of natural gas as the energy inputs or when the current (2022) electric grid mix is used. These inputs contribute a larger fraction of fossil fuel use than scenarios that use more electricity or a grid with a higher fraction of renewable energy. The largest fraction of supply chain contributions is from upstream energy, primarily through electricity use but also a smaller percentage of natural gas that may be used to handle or process a fuel or material input to another stage of the supply chain. Supply chain impacts from these inputs decrease for the scenarios that combine the largely decarbonized 2030 or 2050 grid mix and a larger proportion of electric melting.

3.2 Energy and GHG Emissions Differences for the Combined Glass Sector

The energy and emissions for each sector can also be used to project the total impact for the evaluated glass manufacturing sectors. Figures 7 and 8 show the maximum difference in energy and emissions for the three glass sectors combined. The electric grid is kept the same in the comparison for each year to highlight the effect that technology adoption alone has on energy consumption and GHG emissions. The highest energy and GHG emissions are observed when no improvements are made, and the sectors maintain the baseline energy level. The electric grid mix is held constant for each year. There is a notable increase in both total energy and GHG emissions through 2050 when using the baseline values compared to when using lower energy inputs and alternate energy sources. Fiberglass is a much smaller contribution to total energy and GHG emissions due to the much lower volumes produced than flat glass and container glass. Also, these projections look at current production trends but do not account for the potential increase in demand for flat glass that would be needed if there is increased deployment of photovoltaics during the time frames included for these scenarios (Wikoff, Reese, and Reese 2022). The “maximum improvements” level shows the decreased level of total energy demand and GHG emissions when increasing to 90% cullet use, substituting 20% renewable electricity-based hydrogen in natural gas, using a 50% electric melting furnace, and improving to PM energy consumption levels. Under this more optimistic scenario, we observe a 72% reduction in total energy demand and a 78% reduction GHG emissions.

The scale of glass production selected for Figures 7 and 8 encompasses all U.S. production for the selected glass sub-sectors. Total volumes of glass for each sub-sector use reported values from the Annual Survey of Manufactures for 2020, with a 3% assumed annual production increase for each year through 2050 (US Census Bureau 2021). The technology changes listed as “maximum improvements” will take time to incorporate into all glass manufacturing facilities; the comparison here is included to illustrate the possible reduction in energy and GHG emissions in the year of each electricity grid mix if the listed technologies were integrated into the sector at once.

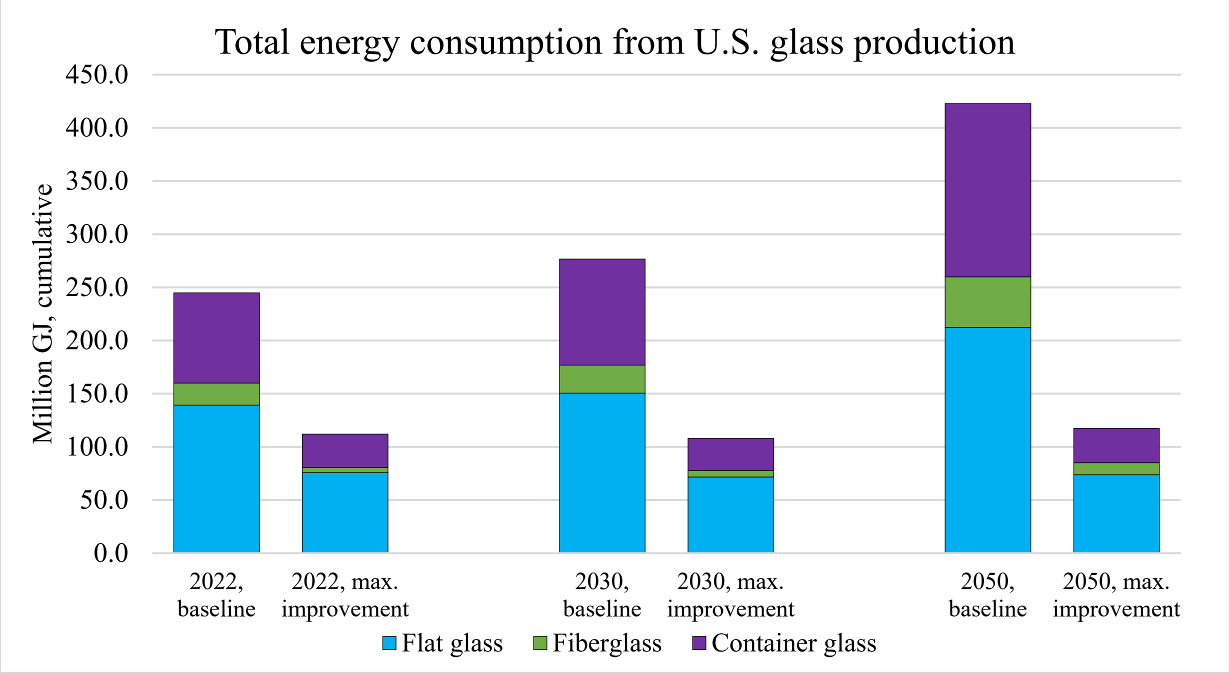

Figure 7. Difference in energy levels for baseline compared to maximum energy level improvements and grid changes, applied to U.S. annual demand for flat, container, and fiber glass sub-sectors

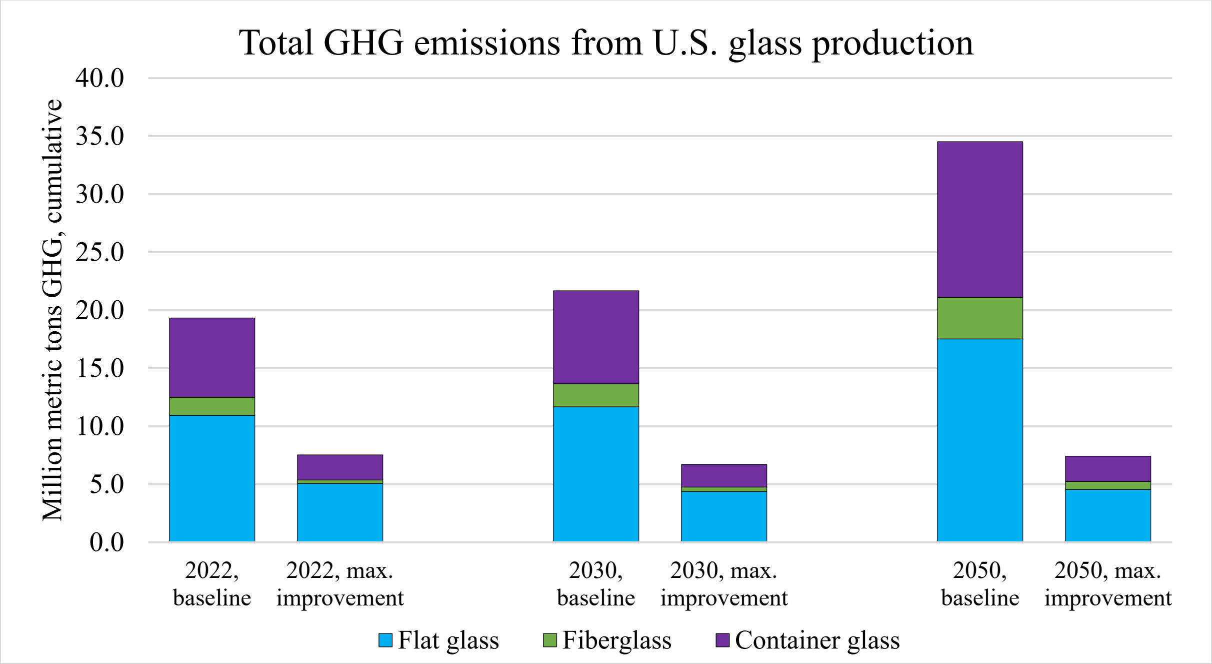

Figure 8. Difference in GHG emissions for baseline compared to maximum energy level improvements and grid changes, applied to U.S. annual demand for flat, container, and fiber glass sub-sectors

4 Discussion

4.1 Technologies Affecting Energy Levels and GHG Emissions

In addition to the trends of lowered GHG emissions and supply chain energy when energy efficiency measures are adopted, there are several points to examine from each sector's results. First is that both overall energy input and GHG emissions increase when switching to a hybrid furnace that uses 50% electricity, even with the ReEDS 2030 grid mix. This is because the 2030 grid still contains a significant fraction of fossil-fuel based energy sources, and fossil fuel sourced electricity has an extra conversion step in the sequence of energy transfer from fuel combustion→ electricity→ glass melt, as opposed to conventional furnaces with the sequence of fuel combustion→ glass melt. The increase is small when switching to a hybrid furnace, as the electric grid in 2030 is projected to be mostly renewable by this point, but it is still larger than the current proportion of fuels or when using renewable electricity-based hydrogen in 2030 (which replaces fossil-fuel natural gas with renewable hydrogen). Glass manufacturers looking to reduce their carbon impact should account for the level of renewable energy in the local electric grid as an important factor when evaluating which decarbonization options would be the most impactful. Energy reduction can be achieved by implementing the improvements listed in Table 2 (page 6), for furnaces not currently using those technologies.

Second is the sizable impact of cullet use for all glass sectors. In theory, cullet acts as a net benefit due to lower energy requirements, reduced virgin raw material inputs, and reduced decomposition CO_2 emissions contributing to GHG totals. In practice, lack of availability, high levels of metal, organic, or polymer contamination, large travel distances between cullet gathering and processing sites, and a lack of infrastructure in some locations can cause cullet to be less desirable for production lines whose goals include a low product rejection rate and output of a consistent on-spec product. Flat glass furnaces typically use low levels of post-consumer cullet (close to the zero percent option listed), with all cullet sourced from pre-consumer (internal) rejects during production or processing (Rue 2018; Geboes 2020). While the reuse of pre-consumer cullet is important for reducing waste, it is also an indicator of inefficiencies in the production process as it represents glass that is processed multiple times before reaching a consumer (compared to external post-consumer, which goes through a complete cycle of use before becoming cullet). Internal cullet is purer and contains fewer contaminants as there is less opportunity for mixing with outside material. External cullet sources require rigorous screening and recovery that is more expensive than leaving glass in a mixed waste stream for landfilling.

Flat glass recovery from its major uses (architectural and automotive) is possible but more expensive than leaving it in the frame at end-of-life (Geboes 2020). Recovery of automotive glass also requires specific separation technology due to the lamination of glass for vehicle use (Šooš et al. 2021; Swain et al. 2015). These factors together lead to nearly nonexistent post-consumer flat glass recycling in the United States. The glass cullet collection and sorting technologies needed to support and enable significantly increased use of cullet would need to be improved, economically viable, and fully evaluated to understand the energy and carbon impacts. Container glass cullet use in the United States averages close to the 30% cullet levels listed (Jacoby 2019; Collins 2017). Other regions (such as Europe) show higher recycling rates, with some locations approaching the 90% level for certain glass colors (FEVE 2022).

Fiberglass uses levels of cullet comparable to those of container glass, although this is primarily from container glass that has not been color-sorted rather than closed-loop fiberglass (Rue 2018). Fiberglass itself is not recycled in large amounts due to processing methods that shorten the fiber length as well as the difficulty in recovering fiberglass from composite materials[4] (Oliveux, Dandy, and Leeke 2015). Fiberglass is currently downcycled when it is recycled[4]. Methods for the recovery and reuse of fiberglass from composites are being researched (Palmer et al. 2009; Oliveux, Dandy, and Leeke 2015) but are not the subject of this analysis. Fiberglass manufacturers have shown interest in cullet because mechanical properties and structure are the main factors determining value rather than appearance, while container and flat glass also must account for quality through the number of visible bubbles and optical qualities of the final product. Higher cullet levels would require a more closed-loop recycling system for each specific glass product as manufacturers have less control over the properties of the final product - glass properties would mirror those of the incoming cullet, and separate recovery schemes for different glass types would ensure that glass quality does not decrease.

4.2 Potential Alternative Technologies for Glass Manufacturing

According to current reports on glass decarbonization, several potential methods for glass energy consumption or GHG emissions reduction have been examined at a research, pilot, or limited commercial scale (Zier et al. 2021; Furszyfer Del Rio et al. 2022; Ireson et al. 2019). Though several of the available technologies overlap with those listed in the glass bandwidth report or the scenarios for this study, the following are not included at this time but are candidates for consideration in future analyses:

- **Thermo-Chemical Heat Recovery:** Thermo-chemical heat recovery is the process of mixing incoming fuel gas with recirculated flue gas to recover heat while creating a mixed stream of syngas fuel. Though this technology is promising due to the lowered cost of a furnace retrofit (Gonzalez et al. 2015), it is not practical for air combustion due to the large volume of nitrogen that would dilute the recirculated flue gas (Zier et al. 2021). Once this technology has been further studied, the potential savings of fuel input could be magnified by adding oxygen regeneration to oxy-fuel firing, preheating the cullet, and combining these technologies for added benefits (Laux et al. 2019). Energy savings are up to 29% when regenerative equipment and preheating technology are installed at an oxy-fuel furnace, as calculated for a 300 ton/day container glass furnace, but this technology has only been installed in a few test locations so far.
- **Biogas as Fuel:** The use of biogas as a supplementary or replacement fuel has been tested in southern Germany (Torrijos 2016), but acceptance of this technology on a larger scale would require a reliable source of fuel with consistent speciation to avoid affecting glass quality (Torrijos 2016; “Biogas Market Size, Share & Growth Forecasts Report 2025” n.d.). Heat and moisture content can affect the oxidation state of the glass melt and quality of the final product. Currently, an insufficient volume of biogas is available to replace a significant portion of natural gas, for glass production or otherwise, and better options are available for carbon reduction that avoid the use of gas combustion entirely. This technology, along with other gas substitutes, can be seen as a halfway measure that still uses gas combustion instead of technologies that reduce the amount of CO_2 produced from glass furnaces.

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[4] Is Fiberglass Recyclable? Who is Recycling Fiberglass? https://designedconscious.com/plastics-in-the-ocean/sustainability-news-stories/is-fiberglass-recyclable-who-is-recycling-fiberglass/

- **Biomass Gasification:** Gasification of biomass to create a synthetic fuel similar to Fischer-Tropsch would have similar issues to biogas combustion, and the resulting gasified fuel would need to have a consistent heat content to maintain the desired furnace melting temperature (Fiehl et al. 2017). This option also runs into the issues that (1) continued use of fuel combustion generates CO_2, (2) biomass land use could potentially compete with edible biomass production and (3) the additional biomass required generates land-use change effects that can negatively affect both carbon emissions and the quality of the soil where the biomass is produced.
- **Hydrogen as Sole Fuel:** Hydrogen as a replacement or supplement to existing natural gas fuel has been widely studied (Ireson et al. 2019; Friedmann, Fan, and Tang 2019), but there are still cost issues and the need for nonfossil fuel sourcing before 100% implementation is possible (Bloomberg New Energy Finance 2020). Hydrogen combustion alone has a different flame length, temperature, velocity, and heat content than natural gas firing, so furnace redesign or changes in the amount of fuel required would also have to be considered[5] (Ditaranto, Anantharaman, and Weydahl 2013). Several scenarios do account for supplementing natural gas with hydrogen instead of a complete replacement, as minor hydrogen inputs would not require the same type of furnace redesign (Ma et al. 2009).
- **Synthetic Methane:** Synthetic methane for use in a glass furnace would be found in the form of syngas from renewable sources. This fuel works as a replacement for natural gas and has fewer performance issues than other technologies, but it retains the problems of higher costs and conversion losses of primary inputs during the methane production process (Zier et al. 2021; Rönsch et al. 2016; Schaffert et al. 2020), as well as the same issues mentioned earlier for biogas or biomass gasification. A lower-carbon feedstock would be needed to make the substitution worthwhile in the balance of GHG reduction.
- **Segmented Melting:** Melting the batch and cullet inputs separately offers minor savings in terms of energy inputs but requires larger costs due to the two loading zones that would now be required. This technology also has higher maintenance requirements and requires more batching adjustments if the proportion of cullet is changed (Worrell et al. 2008).
- **Heat Transfer to Internal/External Sources:** Extra heat from the furnace or forehearth can also be used to heat parts of the plant or sent to heat commercial or residential houses (Fang et al. 2013; Moser, Puschnigg, and Rodin 2020). This option is more likely in urban areas that have more integrated systems for heat transfer or when infrastructure is available to use the waste heat effectively.

4.3 Effects of Individual Technologies on Energy Levels and GHG Emissions

4.3.1 Effect of Hydrogen Blend in Natural Gas

Substituting 20% SMR hydrogen in the natural gas feed while holding all other factors constant increases energy and GHG emissions by an average of 1.6% and 1.0%, respectively, though the effects vary by sector. This is in part because production reflects the current methods for hydrogen generation, with a total of 92% of U.S. hydrogen being produced through SMR, according to S&P Global Market Reports ("Hydrogen - Chemical Economics Handbook" 2021).

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[5] Hydrogen or Electrical Power for a Greener Glass Industry
https://www.eurotherm.com/glass-manufacture/hydrogen-or-electrical-power-for-a-greener-glass-industry/

The hydrogen economy is one pathway that can help decarbonize industries in the United States (Oliveira, Beswick, and Yan 2021), and use of 20% hydrogen blended with natural gas represents a first step along that pathway for the glass industry. The use of hydrogen only reduces energy demand and GHG emissions if it is generated using technologies such as renewably-generated electricity powering electrolysis to split hydrogen from water (i.e. green hydrogen) (Saadat and Gersen 2021). This method is not widespread currently but is viewed favorably for future development due to the decreasing capital cost for electrolysis and lack of CO_2 emissions from the underlying electricity source.

When the same scenario (replacing 20% of gas with H2) is run with renewable hydrogen and the ReEDS 2030 grid, supply chain energy demand decreases by an average of 13.5% across all sectors while emissions drop by 12.6%. The decrease in emissions is largest for the flat glass sector and smallest for container glass, which have the largest and smallest proportion of electricity, respectively, that would be affected by a more decarbonized grid. Part of the difference between energy and emission changes is that GHG totals always include carbonate decomposition, primarily from limestone and soda ash, which is only affected by cullet levels. Renewably generated hydrogen replacement at 20%, along with SOTA energy levels, hybrid glass melting, and the projected grid in 2050 with low RE cost, provides the second-lowest results for energy and emissions after the same scenario but with PM energy levels. 20% volumetric replacement of natural gas with hydrogen equates to replacing 7.3% of the gas energy content when accounting for each fuel's volumetric energy density. This implies that with a decarbonized grid, increased use of renewably generated hydrogen would reduce GHG emissions if furnaces and pipelines can accommodate higher use. It should be noted, though, that using hydrogen formed from electrolysis and renewable electricity is less efficient than using renewably sourced electricity directly, and the combustion of hydrogen can lead to an increase in nitrogen oxide emissions that negatively affect air quality (Saadat and Gersen 2021). Energy justice groups recommend alternate uses for both renewably-sourced hydrogen and renewable electricity, and supplementation of natural gas as a combustion fuel is not one of the more favorable options (Saadat and Gersen 2021).

4.3.2 Effect of Cullet Level

With respect to the results from MFI, adding 30% cullet with SOTA energy levels yields a larger decrease in total energy and GHG emissions compared with improving to PM energy levels alone, or SOTA energy levels with the 2030 ReEDS grid. This is a change that requires input from (1) consumers, who must be incentivized to recycle glass, when possible, (2) recyclers, who must produce cullet that meets furnace specifications, and (3) industry that can help fund infrastructure and create opportunities for recycling. Table 3 shows the average decrease in total energy consumption levels and GHG emissions for each sector, both when adding one level of cullet (as shown in Figures 1-6) and overall compared to when no cullet is used. The average is across all scenarios for a given cullet level and sector to show the role cullet plays regardless of additional scenario changes.

Table 3. Decreases in Total Energy and GHG Emissions for Each Glass Sector When Cullet Levels are Increased

Values are averages for each cullet level and sector for each of the 10 scenarios. Emissions refer to GHG emissions as reported by MFI as well as CO_2 material losses.

Change in cullet levels	Flat		Container		Fiber	
	Energy	Emissions	Energy	Emissions	Energy	Emissions
0 → 30% cullet	10.4%	16.6%	16.8%	21.9%	7.8%	12.6%
0 → 90% cullet	37.5%	58.4%	57.0%	71.5%	27.0%	50.7%
30 → 90% cullet	28.7%	48.5%	48.2%	63.3%	19.8%	42.4%

4.3.3 Effect of Decarbonized Electric Grid

Also, the effect of improving the profile of contributions to the electric grid should not be overlooked. The improvements of this change can be seen in two direct ways among the selected scenarios when comparing results where the only change is the electric grid mix:

- Comparing SOTA energy levels with the 2022 grid to SOTA with the ReEDS 2030 grid
- Comparing SOTA energy levels with 50% electricity and 20% RE hydrogen, shifting from the ReEDS 2030 to ReEDS 2050 grid

Each of these comparisons shows a decrease in energy levels and GHG emissions across all glass sectors, with the inputs of cullet and energy level, material inputs, and fuel source being held constant. The smallest improvements from the ReEDS grid scenarios come when normal levels of electricity are used for glass manufacture (i.e., when 50% electricity is not used). This makes sense because there should naturally be a larger decrease in energy emissions due to the electric grid when a larger percentage of electricity is used. Table 4 shows how the energy and GHG emissions for each sector decrease when switching to the ReEDS 2030 or 2050 grid projections, using an average across all cullet levels. The savings listed only reflect a switch to the projected energy grid; they do not show the effect of adjusting energy levels in the glass manufacturing process or switching fuel sources.

Table 4. Decreases in Total Energy and GHG Emissions for Each Glass Sector when ReEDS Electricity Grid Mixes are Used in Place of the 2022 U.S. Grid

Values are averages for each cullet level and sector. Emissions refer only to GHG emissions as reported by MFI. ReEDS 2030 and 2050 refer to the grid mix in each year when following the ReEDS scenario with a 95% GHG reduction below 2005 levels by 2035 and net zero emissions by 2050.

Reference Scenario and Grid Projection	Flat		Container		Fiber	
	Energy	Emissions	Energy	Emissions	Energy	Emissions
SOTA energy level, 2022→ReEDS 2030	12.9%	13.7%	6.7%	6.3%	6.6%	7.0%
SOTA energy level, ReEDS 2030→2050 and 20% RE H_2	38.2%	32.1%	32.2%	26.0%	40.0%	34.0%

Flat and fiber glass show greater reductions in both energy and emissions when implementing the ReEDS projections due to their overall higher energy use relative to container glass. Each of these products has higher life cycle energy inputs across all stages of production due to higher energy in either processing, purity, or forming operations. The projected grid changes for 2030 and 2050 are essentially a requirement for significant reduction of energy levels and decarbonization of glass. Less-aggressive ReEDS projections with higher carbon intensity would yield lower levels of emission and energy reduction. When cullet levels are at 90%, energy inputs are at PM levels, renewably-generated hydrogen replaces 20% of the natural gas volume flow, and 50% furnace electricity is used with the ReEDS 2050 grid mix, total energy demand is 76%-83% lower than the baseline inputs for each sector. GHG emissions are 80%-86% lower. These reductions would be closer to net-zero with a 100% electric furnace, even if the required technology is currently further from commercialization for some sectors. To fully decarbonize, no fossil fuel combustion can be used at any point in the glass manufacturing process unless carbon capture is also utilized. 90% external cullet levels eliminate most (but not all) CO_2 losses from carbonates, which would also require carbon capture or material replacement to fully decarbonize.

Energy efficiency improvements and hybrid furnace adoption are two changes that glass manufacturers could implement now and would show immediate reductions in energy demand and GHG emissions, as long as a renewable source of electricity is in use. An increase in cullet levels would require a shift in end-of-life handling practices for each sector to reach consistently high recycling rates, but would require less effort to maintain once in place. Hydrogen has a few successful test cases, but it is not deployed widely at the levels listed yet and needs significant scale-up of renewable production methods.

5 Conclusions

Energy consumption and GHG emissions are lowered by improving either direct energy input, through technological improvements from Table 2; decarbonizing the electric grid mix, as shown through ReEDS scenarios that include policy drivers; or reducing fossil fuel input, as demonstrated with electric melting and renewably-generated hydrogen.

Energy efficiency measures are highly impactful when natural gas is a larger proportion of the energy inputs, and such measures help lower supply chain energy demand in all scenarios. Any renewable electricity that can replace natural gas should reduce both energy demand and emissions. Decarbonization of the U.S. electricity supply will reduce energy and emissions profiles for all glass types, though this is primarily out of the hands of glass manufacturers unless there is the desire to source renewable electricity prior to changes made by the state or municipality. Materials have a smaller influence than direct energy inputs, though they are more prominent when counting GHG emissions and the CO_2 emissions from raw material decomposition. Increasing cullet levels will yield energy savings and reduce raw material use and carbonate decomposition, though this requires the establishment of systems to procure, clean, and transport cullet reliably. These systems would, in turn, require additional investment for securing nearby cullet streams, contracting (or requiring business expansion) for cullet cleaning and transportation, and adjusting product recipes to account for the presence of recycled material. Though there are proven benefits to cullet use via increased furnace longevity due to the reduced thermal stresses, there are still cost and risk barriers in the United States to overcome before making this change. Without cullet, carbon capture of the flue gas stream would be required to decarbonize the process completely, which is not considered in this analysis.

Despite variations in the specific type of product produced, there are still similarities between the sub-sector results. Each glass sub-sector showed the same trends of a reduction in energy and emissions when manufacturing energy levels were lowered or the grid was decarbonized, and a gradual decrease as the electric grid evolves. The magnitude of the improvements depends on the degree of reduction in direct energy input, which is different for each sub-sector, as well as the fraction of electricity used and the variation in raw materials. Each sub-sector would reduce energy consumption and emissions via the strategies included in the scenarios examined in this report, which would also provide an economic benefit by reducing the total costs of fuel and potential future penalties for increased CO_2 emissions.

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Appendix. Technologies Included in Reduced Energy Levels, ReEDS Grid Projections, and Values for All Report Figures

The following table includes details from Table A4-1 of the glass bandwidth report, which lists the technologies included in the State-of-the-Art and Practical Minimum energy levels. Following the table is a brief description from the glass bandwidth report on how the energy reductions were applied to each general energy level for each sub-sector. These energy levels are the values used for the corresponding energy levels in the scenarios for this report as entered into each recipe for MFI.

Table A-1. Technologies Included in Glass Energy Levels, as Described in the Glass Bandwidth Report

Technology	Description	Stage	Estimated Savings (%)	Included in SOTA Energy Levels?	Included in PM Energy Levels?
Motor resizing or variable speed drives	Motors and pumps can be purchased for a cheaper price at a generic size, rather than one specific to each furnace. This causes energy losses that could be avoided with an appropriately sized device.	Batching & forming	11.5%	Yes	Yes
New grinding technology	This technology uses continuously operating centrifugal ball mills with a vertical axis and continuous operation are one example of a more efficient grinding method.	Batching	5%	No	Yes
Increased cullet rate	Clean cullet reduces melting energy requirements.	Melting	10%	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	No
Reduced batch wetting	Water is added to the glass batch to reduce dust excess mixing in the batch during transport, which increases energy use due to evaporation in the furnace.	Melting	1%	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	Glass melting energy intensity estimates for all glass sub-sectors are from literature and do not account for reduced wetting.

Technology	Description	Stage	Estimated Savings (%)	Included in SOTA Energy Levels?	Included in PM Energy Levels?
Batch and cullet preheating (and other waste heat recovery)	Waste heat preheats incoming cullet, as opposed to its typical use of preheating combustion air.	Melting	12%	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	No for all other sub-sectors, though possible with any glass.
Minimizing of excess air in furnace	Excess air relative to the amount of required fuel reduces furnace efficiency, reduce excess air to reduce energy input.	Melting	12%	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	Furnace energy for flat, container, and glass fibers are literature values and do not account for this technology if the literature value does not include it (though future use is always possible).
Low-NOx burner	Low-NOx burners can increase heat transfer rates and reduce flame temperatures to increase furnace efficiency.	Melting	5%	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	Furnace energy for flat, container, and glass fibers are literature values and do not account for this technology if the literature value does not include it (though future use is always possible).
Improved heat transfer/ containment	Better insulation, seals, and pressure control can each reduce energy losses in the furnace	Melting	20%	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	Furnace energy for flat, container, and glass fibers are literature values and do not account for this technology if the literature value does not include it (though future use is always possible).
Microwave melting	Microwave energy is used for targeted melting.	Melting	N/A	No. Glass melting energy uses reported best practices, which can include technologies listed here but are not added separately.	Furnace energy for flat, container, and glass fibers are literature values and do not account for this technology if the literature value does not include it (though future use is always possible).
Heating control systems	Advanced sensors and control systems enable continuous monitoring and optimization of heat inputs for fuel savings.	Melting/ glass wool and glass fiber finishing (drying)	3%	Yes, for glass fiber drying, no for flat and container glass due being directly literature-based values.	Yes, for glass wool and glass fiber finishing (drying). Glass melting energy intensity estimates for flat glass, container glass, glass wool, and glass fibers were obtained from the literature- they were not calculated.

Technology	**Description**	**Stage**	**Estimated Savings (%)**	**Included in SOTA Energy Levels?**	**Included in PM Energy Levels?**
Segmented glass melter	Batch materials (electric melter) are melted separately from the cullet (oxy-fuel). This results in lower emissions and increases thermal efficiency.	Melting	N/A	No. Glass melting SOTA energy intensity estimates for all glass sub-sectors were obtained from the literature and not directly calculated.	Yes
Submerged combustion melting	Gas is fired directly into the glass melt, which improves heat transfer and convective stirring. The reduced energy intensity is from less time in the furnace due to the use of segmented melting.	Melting	Range of 5%–7.5% savings, average of 6.3%	No. Glass melting SOTA energy intensity estimates for all glass sub-sectors were obtained from the literature and not directly calculated.	Glass melting energy intensity estimates for flat glass, container glass, and glass fibers were obtained from the literature.
Process controls in forehearths	Forehearth process control such as gob weight in container glass or tin bath temperature in float glass reduce the number of rejects and can save energy.	Forming	3.5%	Yes	Yes
Compressor controls for forming operations	Modulating control of the compressor varies pressure based on flow requirements, and can reduce the energy needed for air compression.	Forming	10%	Yes, for container glass.	Yes, for container glass.
More-efficient forehearths or oxy-fuel-fired forehearths	Replacing existing forehearths with energy-efficient options.	Forming	12% for glass fibers; 4% for other glass sub-sectors.	No	Yes
Improved fiber drying and curing	Drying of molten fibers takes a significant amount of time; advanced technology can speed up the process.	Post-processing (glass wool & fiber)	30%	No	Yes, for glass wool and glass fiber drying.

Technology	Description	Stage	Estimated Savings (%)	Included in SOTA Energy Levels?	Included in PM Energy Levels?
Radio frequency laminating in autoclaves	Radio frequency lamination can reduce processing time (and therefore energy) in an autoclave.	Finishing (flat glass)	4.5%	No	Yes, for flat glass.
Optimized annealing process	Investment in adjusting the annealing lehr, conveyors, receivers, burners, control systems, product loaders, insulation, and other components.	Finishing (flat glass)	2.5% for flat glass 38% for container glass	Yes, for flat and container glass,	Yes, for flat and container glass.
New glass tempering technology with more efficient quenching	New tempering technology design with an improved heat transfer coefficient allows for glass tempering energy and air pressure.	Post-processing (flat glass)	19%	No	Yes, for flat glass.

From the Glass bandwidth report (DOE (U.S. Department of Energy) 2017):

“The SOTA technologies included in this analysis and assumed energy savings were:

- Motor resizing or variable speed drives: 12% savings in batching and forming processes
- Process controls in forehearths (or temperature controls in tin bath, for float glass): 3.5% savings in the forming process
- Compressor controls for forming operations: 10% savings in the forming process
- Optimization of the annealing process: 3%–38% savings in the finishing process.

The PM technologies included in this analysis and assumed energy savings were:

- Motor resizing or variable speed drives: 12% savings in batching and forming processes
- New grinding technologies: 6% savings in the batching process
- Process controls in forehearths (or temperature controls in tin bath, for float glass): 3.5% savings in the forming process
- Compressor controls for forming operations: 10% savings in the forming process
- More-efficient forehearths or oxy-fuel-fired forehearths: 4%–12% savings in the forming process
- Optimization of the annealing process: 3%–38% savings in the finishing process
- Improved fiber drying systems: 30% savings in the finishing process
- Radio frequency laminating in autoclaves: 5%–30% savings in the finishing process
- New tempering technology with more-efficient quenching: 19% savings in the finishing process.

The ReEDS grid mixes used in this analysis are part of the National Renewable Energy Laboratory's Standard Scenarios, which are described in a 2021 report providing insight into how the electric grid could look in future years depending on the costs of generation methods and the push for renewable electricity generation methods (Cole et al. 2021). The selected projections are for 2030 and 2050, and they represent a pathway where GHG emissions are reduced by 95% below 2005 levels by 2035 and a net zero emissions profile is achieved by 2050. The ReEDS grids in 2030 and 2050 include contributions from each electric generation method with this emissions trajectory in mind. The aforementioned pathway is selected because it aligns most closely with the Biden administration's goals for net-zero electric emissions by 2035 (The White House 2021). As described in the report, "the Standard Scenarios are not designed to analyze specific administration goals or targets (such as the Biden administration goal to decarbonize the power sector by 2035), and as such, analysis of specific goals has been left to separate work." Table A-2 shows the composition of the 2030 and 2050 grids used in this analysis.

Table A-2. Projected ReEDS Electric Grid in 2030 and 2050 with the Standard Scenario Definitions Involving Power Sector CO_2 Emissions that are Reduced by 95% (Relative to 2005 Levels) by 2035 and Net Zero by 2050

Generation Method	Percentage of Total Generation, 2030	Percentage of Total Generation, 2050
Solar	17.38%	47.70%
Wind	23.89%	33.40%
Nuclear	16.79%	9.80%
Hydropower	6.60%	3.96%
Natural gas	29.37%	3.74%
Geothermal	0.53%	0.80%
Biomass	0.03%	0.31%
Fuel oil and residue	0.93%	0.16%
Coal	4.35%	0.13%
Diesel	0.00%	0.00%
Concentrating solar power	0.12%	0.00%

The projections for 2030 and 2050 that estimate the total energy use and GHG emissions from the glass sub-sectors examined in the study use a 3.0% increase in demand from each year starting with 2050. The tons of demand for each sub-sector in 2020 are derived from the glass bandwidth report as well as the Annual Survey of Manufactures for 2020 (US Census Bureau 2021). Baseline energy use for each sub-sector refers to each ton of glass produced with the baseline energy inputs for that sub-sector, with none of the technological improvements applied. The "maximum improvement" energy use for each sub-sector accounts for increasing to 90% cullet use, replacing 20% RE hydrogen in natural gas, using a 50% electric input furnace, decreasing to PM energy inputs, and switching to the ReEDS 2050 grid. While it is likely that baseline energy levels will decrease in future years, the comparison shown here is meant to illustrate the largest feasible difference between the two pathways.

Table A-3. Total Energy Inputs and GHG Emissions for Glass Sub-Sectors of Interest in 2022, 2030, and 2050

Year	Glass Sub-Sector	Supply Chain Energy Use (Million GJ)		GHG Emissions (Million tons CO_2-equivalent)	
		2022, Baseline	**2022, Max. improvements**	**2022, Baseline**	**2022, Max. improvements**
2022	**Flat**	131.2	30.4	10.3	1.9
	Fiber	19.6	4.6	1.5	0.3
	Container	80.0	13.5	6.4	0.9
		2030, Baseline	**2030, Max. improvements**	**2030, Baseline**	**2030, Max. improvements**
2030	**Flat**	176.3	40.9	13.9	2.5
	Fiber	26.3	6.2	2.0	0.4
	Container	107.5	18.1	8.7	1.2
		2050, Baseline	**2050, Max. improvements**	**2050, Baseline**	**2050, Max. improvements**
2050	**Flat**	318.5	73.8	25.0	4.6
	Fiber	47.6	11.3	3.5	0.7
	Container	194.2	32.7	15.6	2.2

Table A-4. Estimated and Projected Glass Production (tons/year) for Each Sub-Sector in 2022, 2030, and 2050

Sub-Sector	2022	2030	2050
Flat	7,182,000	9,652,000	17,433,000
Fiber	1,343,000	1,806,000	3,260,000
Container	7,259,000	9,756,000	17,620,000

Table A-5. Energy and GHG Emissions for Container Glass Scenarios

Scenario Details	Total Energy (GJ/ton)	GHG Emissions (kg CO_2e/ton)
0% cullet baseline	11.0	887
0% cullet SOTA opportunity	7.2	659
0% cullet PM opportunity	6.9	642
0% cullet SOTA, 20% H2	7.2	664
0% cullet SOTA, ReEDS grid 2030	6.7	620
0% cullet SOTA, hybrid ReEDS 2030	6.9	633
0% cullet SOTA, ReEDS 2030 RE H2	6.5	608
0% cullet SOTA, hybrid ReEDS 2030 RE H2	6.8	625
0% cullet SOTA, hybrid ReEDS 2050 RE H2	5.0	519
0% cullet PM, hybrid ReEDS 2050 RE H2	4.9	510
30% cullet baseline	9.6	730
30% cullet SOTA opportunity	6.0	518
30% cullet PM opportunity	5.5	487
30% cullet SOTA, 20% H2	6.0	522
30% cullet SOTA, ReEDS grid 2030	5.6	483
30% cullet SOTA, hybrid ReEDS 2030	5.8	495
30% cullet SOTA, ReEDS 2030 RE H2	5.5	472
30% cullet SOTA, hybrid. ReEDS 2030 RE H2	5.8	495
30% cullet SOTA, hybrid ReEDS 2050 RE H2	4.1	397
30% cullet PM, hybrid ReEDS 2050 RE H2	4.0	389
90% cullet SOTA, hybrid ReEDS 2030 RE H2	3.5	220
90% cullet SOTA, hybrid ReEDS 2050 RE H2	2.0	133
90% cullet PM, hybrid ReEDS 2050 RE H2	1.9	125

Table A-6. Energy and GHG Emissions for Flat Glass Scenarios

Scenario Details	Total Energy (GJ/ton)	GHG Emissions (kg CO2e/ton)
0% cullet baseline	18.3	1436
0% cullet SOTA opportunity	13.9	1168
0% cullet PM opportunity	12.7	1092
0% cullet SOTA, 20% H2	14.2	1185
0% cullet SOTA, ReEDS grid 2030	12.2	1021
0% cullet SOTA, hybrid ReEDS 2030	12.6	1039
0% cullet SOTA, ReEDS 2030 RE H2	11.8	994
0% cullet SOTA, hybrid ReEDS 2030 RE H2	12.3	1021
0% cullet SOTA, hybrid ReEDS 2050 RE H2	8.0	767
0% cullet PM, hybrid ReEDS 2050 RE H2	7.3	730
30% cullet baseline	16.7	1246
30% cullet SOTA opportunity	12.8	1001
30% cullet PM opportunity	11.4	921
30% cullet SOTA, 20% H2	12.9	1120
30% cullet SOTA, ReEDS grid 2030	11.0	852
30% cullet SOTA, hybrid ReEDS 2030	11.3	870
30% cullet SOTA, ReEDS 2030 RE H2	10.6	827
30% cullet SOTA, hybrid. ReEDS 2030 RE H2	11.0	853
30% cullet SOTA, hybrid ReEDS 2050 RE H2	7.0	609
30% cullet PM, hybrid ReEDS 2050 RE H2	6.3	574
90% cullet SOTA, hybrid ReEDS 2030 RE H2	8.5	516
90% cullet SOTA, hybrid ReEDS 2050 RE H2	4.8	294
90% cullet PM, hybrid ReEDS 2050 RE H2	4.2	262

Table A-7. Energy and GHG Emissions for Fiberglass Scenarios

Scenario Details	Total Energy (GJ/ton)	GHG Emissions (kg CO_2e/ton)
0% cullet baseline	14.6	1082
0% cullet SOTA opportunity	9.4	768
0% cullet PM opportunity	8.3	700
0% cullet SOTA, 20% H2	9.6	775
0% cullet SOTA, ReEDS grid 2030	8.8	718
0% cullet SOTA, hybrid ReEDS 2030	9.3	744
0% cullet SOTA, ReEDS 2030 RE H2	8.4	691
0% cullet SOTA, hybrid ReEDS 2030 RE H2	9.0	729
0% cullet SOTA, hybrid ReEDS 2050 RE H2	5.6	523
0% cullet PM, hybrid ReEDS 2050 RE H2	5.0	489
30% cullet baseline	13.6	973
30% cullet SOTA opportunity	8.8	679
30% cullet PM opportunity	7.6	613
30% cullet SOTA, 20% H2	8.9	688
30% cullet SOTA, ReEDS grid 2030	8.2	629
30% cullet SOTA, hybrid ReEDS 2030	8.6	654
30% cullet SOTA, ReEDS 2030 RE H2	7.7	604
30% cullet SOTA, hybrid. ReEDS 2030 RE H2	8.4	640
30% cullet SOTA, hybrid ReEDS 2050 RE H2	5.1	442
30% cullet PM, hybrid ReEDS 2050 RE H2	4.5	410
90% cullet SOTA, hybrid ReEDS 2030 RE H2	7.0	424
90% cullet SOTA, hybrid ReEDS 2050 RE H2	4.0	243
90% cullet PM, hybrid ReEDS 2050 RE H2	3.5	212