

Life-Cycle Analysis Update of Glass and Glass Fiber for the GREET™ Model

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ACRONYMS

CFGF	continuous filament glass fiber
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GFRC	glass fiber reinforced composite
GHG	greenhouse gas
LCA	life-cycle analysis
LCI	life-cycle inventory
PM	particulate matter
USGS	U.S. Geological Survey

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1 INTRODUCTION

The glass industry accounts for 1% of the total energy consumption by the industrial sector in the U.S. (EIA 2013). In 2013, the product shipments value of the U.S. glass industry totaled \$28.32 billion (U.S. Census Bureau 2013). There are four major sectors of glass: container glass, flat glass, glass fiber and specialty glass. Container glass primarily serves as the packaging material for food and beverages. Flat glass finds major applications in windows for buildings and automobiles. Glass fiber can be further divided into two sub-sectors: textile glass fiber and glass wool. The former is used as reinforcing materials for composites, while the latter is used as insulation materials for construction. Specialty glass ends up in a wide variety of products ranging from cookware to television tubes (DOE 2002).

This study analyzes the life-cycle impacts associated with the U.S. production of flat glass and textile glass fiber. The system boundary is cradle-to-gate, starting with raw material extraction, and ending with manufacturing of glass products. The life-cycle inventories (LCIs)

for flat glass and textile glass fiber are compiled based on data available in recent literature, with a cut-off criteria of 1%. The updated LCIs are to be incorporated into the 2015 version of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.

2 FLAT GLASS

The flat glass sector accounts for around 25% of the energy consumption of the glass industry (EIA 2013). Safety and security glass, which is mostly used in vehicles, represents more than 2/3 of the U.S. demand for high-performance flat glass in 2012. Solar control glass, mainly used in buildings accounts for 22.5%. The demand is projected to rise to 910 million square feet in 2017, at an annual growth rate of 4.4%, as a result the rebound of new building construction and increasing penetration of laminated glass into the side windows of automobiles (Ceramic Industry 2013a).

2.1 Production of Flat Glass

The generic glass production process typically consists of four stages: batch preparation, melting and refining, forming, and post-forming (DOE 2002). During the batch preparation stage, batch materials are ground into desired sizes and mixed in prescribed proportions, which differ for different types of glass. The pretreated batch materials are then charged into the furnace where the materials decompose and form the crystalline network of glass at elevated temperatures. The refining process also occurs in the furnace, when the molten glass is homogenized and conditioned after it is freed of bubbles. Following the melting and refining stage, the refined glass undergoes forming for it to be shaped into the final forms. Further finishing treatments, which comprise the post-forming stage, are subsequently applied to the shaped glass to develop desirable characteristics of the final products (Worrell *et al* 2008). The batch preparation stage is similar, if not identical, across different glass sectors. So is the melting and refining stage. The forming and post-forming stages tend to take different forms depending on the type of glass (DOE 2002).

Flat glass for automotive applications is almost exclusively produced by the float glass process (Worrell *et al* 2008), which is characterized by pouring the conditioned molten glass onto a molten tin (known as the float bath) so that the glass spreads on the bath and forms a flat ribbon. The floating ribbon is then cooled, lifted out by conveyor rollers, and sent to the

annealing lehr (Scalet *et al* 2013). For automotive glass, additional post-forming treatments may be necessary, such as tempering and laminating. Tempering involves heating and quenching the glass, while laminating involves sandwiching two pieces of glass with plasticized polyvinyl butyral (PVB) resin and autoclaving (DOE 2002). The production process of automotive glass is depicted in Figure 1.

2.1.1 Material Inputs for Float Glass Production

Batch material feed dominates the material inputs associated with glass production. Batch material requirements depend upon the glass composition, which varies by the glass being manufactured as aforementioned. For flat glass produced by the float glass process (a.k.a. float glass), the average composition is 72.12 wt% SiO_2 , 13.56 wt% Na_2O , 8.64 wt% CaO , 4.03 wt% MgO and 1.65 wt% others (Smrček 2010). Batch material inputs are derived from the glass composition based on stoichiometric calculation. Glass sand serves as the raw batch material for SiO_2 , soda ash for Na_2O , limestone for CaO , and dolomite for both MgO and CaO (Wallenberger 2010).

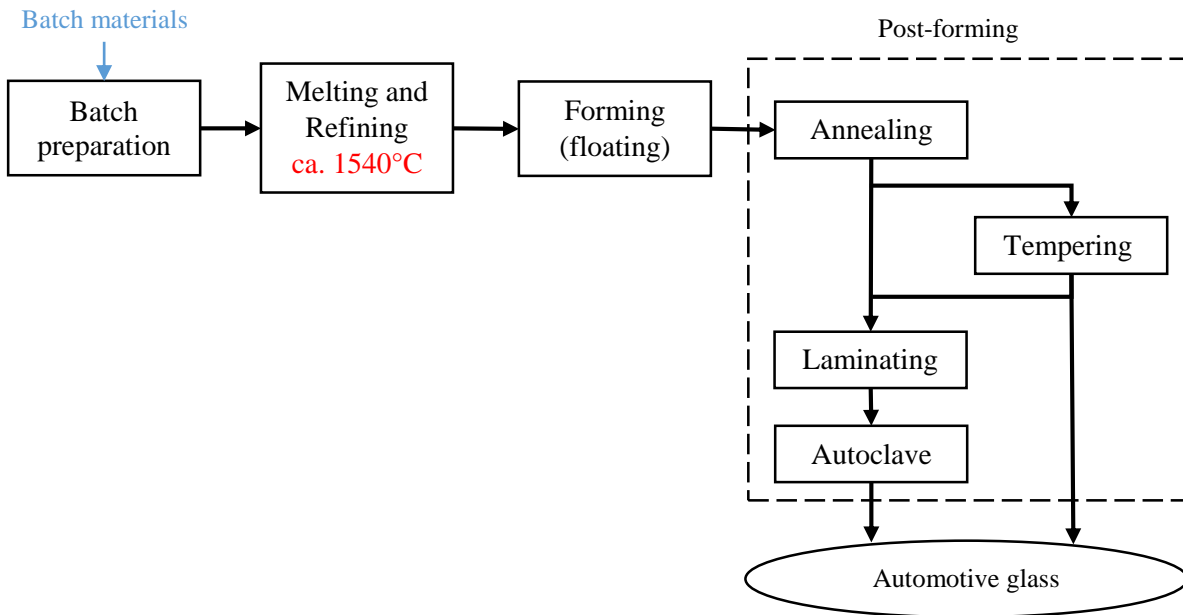


Figure 1. Schematic of automotive glass production

In addition to batch materials, the production of float glass also requires considerable amount of water. Around 5 wt% of water is added to the glass sand to wet the batch. Batch wetting helps to prevent batch segregation during the mixing and charging process, and reduce dusting problems (Bingham 2010). Water used for batch wetting is completely lost through evaporation during the melting and refining process. Compared with the batch preparation process, the post-forming process features significantly higher water use, estimated to be over 360 gallons/ton of glass produced, for cooling and cleaning of the glass ribbon coming out of thelehr (Scalet *et al* 2013). Although part of the cooling water is evaporated, the remaining water can be closed-loop recycled or reused because it is not contaminated. In this study, it is assumed that cooling and cleaning water is neither recycled nor reused. Therefore, the water consumption estimated represents the worst case scenario for the float glass production.

2.1.2 Energy Inputs for Float Glass Production

Since glass production is an energy-intensive process, its energy consumption has been examined in literature (Ruth *et al* 1997, DOE 2002, Rue *et al* 2007, Worrell *et al* 2008, Wallenberger 2010, Scalet *et al* 2013). Energy inputs for float glass production as reported in existing studies are summarized in Table 1. The energy input for the melting and refining stage changes with furnace size and furnace type, and is given as a range if possible.

Table 1. Energy consumption for flat glass production (MMBtu/ton)

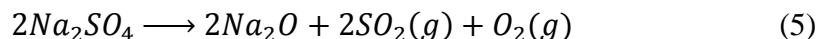
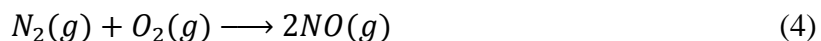
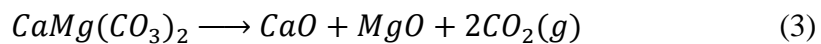
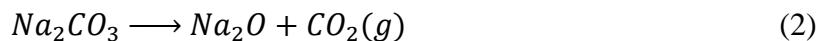
Processing stage	Ruth et al 1997	DOE 2002	Rue <i>et al</i> 2007	Worrell <i>et al</i> 2008	Wallenberger 2010	Scalet <i>et al</i> 2013
Batch preparation	0.27	0.27	0.68	0.3	---	---
Melting and refining	8.1	6.5-8.8	5-7.5	5.4-8.8	4.3	6.45
Forming	1.45	1.5	1.5	1.5	---	---
Post-forming	2.2	6.26	2.2	6.26	---	---

As can be observed from Table 1, the melting and refining process dominates the total energy consumption associated with float glass production, followed by post-forming, forming and batch preparation. Batch preparation and forming processes are solely powered by electricity, while post-forming and melting and refining processes are almost exclusively fueled by natural gas (DOE 2002). Because float glass production is a well-established technology, the

energy consumptions for batch preparation, forming and post-forming reported in different studies are comparable. In contrast, the energy consumption for melting and refining has decreased over the last decade, as a result of the ongoing effort by the glass industry to improve the energy efficiency through the adoption of regenerative furnace and electrical boost (Rue *et al* 2007, Wallenberger 2010, Scalet *et al* 2013). As the energy consumption for melting and refining reported by Rue *et al* is based on surveys and interviews conducted by the authors with major glass manufacturers in the U.S. (Rue *et al* 2007), the industrial average they estimated, 6.5MMBTU/ton, is chosen to be incorporated into this GREET update.

2.1.3 Emissions from Float Glass Production

The production of float glass gives off emissions of various criteria pollutants. The batch preparation process handles fine ground particles and therefore emits particulate matter (PM). However, since most modern mixing vessels are equipped with filter systems which virtually capture all PM emissions (Scalet *et al* 2013), the PM emission from batch preparation is assumed to be negligible. During the melting process, batch materials decompose and give off CO₂ emissions (Reactions 1, 2, 3). The quantity of CO₂ emitted is estimated by stoichiometric calculation. Due to the high temperature in the furnace, nitrogen in the air reacts with oxygen to produce thermal NO_x (Reaction 4), which starts to form at temperatures greater than 760°C and is generated to the limit of available O₂ at temperatures greater than 1300°C (EPA 1999). SO_x is also emitted from the melting and refining process, as a result of thermal decomposition of Na₂SO₄ (Reaction 5), which is used as the refining agent (Bingham 2010).



The controlled emissions from the melting and refining of float glass assuming state-of-the-art abatement technologies are reported by Scalet *et al*. As the emissions they reported

include the emissions from combustion of natural gas used in the furnace (Scalet *et al* 2013), the process emissions are approximated by subtracting the natural gas combustion emissions calculated using 2014 GREET emissions factors for industrial natural gas boilers, from the reported emissions by Scalet *et al*.

The only emission of concern from the forming and post-forming stages is associated with the SO₂ sprayed on the hot ribbon to protect it against the rollers before it enters thelehr. The ensuing SO_x emission is estimated to be 18-36 grams/ton of glass produced (Scalet *et al* 2013).

2.2 Summary

Table 2. LCI for automotive glass production

	Batch preparation	Melting and refining	Forming	Annealing	Tempering	Laminating*
Energy inputs (MMBtu/ton)						
Natural gas	---	6.37	---	0.4	4.01	1.5
Electricity	0.27	0.13	1.5	0.01	0.19	0.14
Material inputs						
Sand (ton/ton)	0.721	---	---	---	---	---
Limestone (ton/ton)	0.099	---	---	---	---	---
Soda ash (ton/ton)	0.232	---	---	---	---	---
Dolomite (ton/ton)	0.183	---	---	---	---	---
Water (gal/ton)	8.64	---	---	360	---	---
Emissions (g/ton)						
CO ₂ **	---	205,963	---	---	---	---
NO _x	---	766	---	---	---	---
PM	---	---	---	---	---	---
SO _x	---	452	---	18	---	---

* Includes autoclave

** Based on stoichiometric calculation

The updated LCI for the production of float glass for automotive applications is presented in Table 2.

In addition to the automotive glass, LCI is also compiled for dolomite, because it is a batch material for float glass, but is not available in 2014 GREET. Energy inputs for the mining and transportation of dolomite is obtained from Ramakrishnan and Koltun, which is based on the magnesium production in China (Ramakrishnan and Koltun 2004), and serves as one of the data sources for the magnesium LCI in 2014 GREET (Johnson and Sullivan 2014).

3 TEXTILE GLASS FIBER

Textile glass fiber is also known as continuous filament glass fiber (CFGF). It is primarily used as the reinforcement of a matrix to form composites (Pico *et al* 2012). The global consumption of textile glass fiber was about 4 million metric tons (Mt) in 2011 (Pico *et al* 2012), and it is projected to reach 4.5 Mt in 2018 (Ceramic Industry, 2013b). Increasing demands for textile glass fiber in the construction, automotive, and equipment manufacturing industries are expected to lead the growth (Ceramic Industry 2013b).

Among the different types of textile glass fibers, E-glass is the most widely used for composites applications, and represents more than 99% of the textile glass fiber market (Wallenberger 2010).

3.1 E-glass Production

The batch preparation and melting and refining stages of the E-glass production process are fundamentally the same as those of the float glass production, except that the furnace temperature for E-glass is about 140°C lower as a result of different batch composition (Pico *et al* 2012), and the furnace is not regenerative due to economic and environmental concerns (Scalet *et al* 2013). The E-glass production is characterized by its unique forming and post-forming processes. After refining, the molten glass flows to bushings, where it is drawn through openings in the bushings by a mechanical force to be fiberized. The bushings are typically made of platinum-rhodium alloys and contain 400-8000 holes with a diameter of 1-2.5mm. Due to the high temperature of the molten glass, the bushings are subjected to aging, and need to be replaced every 250-350 days (Stiller 1999).

Immediately after leaving the bushings, the fibers are subjected to rapid cooling by air and water spray (Pico *et al* 2012). The diameters of the resultant filaments range from 4 to 40 μm . To protect and lubricate the brittle filaments, a coating, also referred to as size, is applied to the fibers before they enter the subsequent post-forming processes. The size applied also dictates the performance of the fibers in a composite, notably the interface interaction between the matrix

and the filaments. The size is generally an aqueous mixture of polymers, lubricants, coupling agents and additives. The exact composition, however, depends on the glass fiber being manufactured, and remains proprietary (Woude and Van der Lawton 2010). After sizing, the filaments are wound into a spun. Based on final application, additional post-processing steps may follow, such as roving assembly, twisting, strand chopping, etc. (Pico *et al* 2012). The production process of E-glass is shown in Figure 2.

In 2012, Glass Fiber Europe conducted a life-cycle analysis (LCA) study for CFGF production in the European countries, which features 2010 data collected from 13 CFGF manufacturers in Europe, representing 95% of the European production volume (PWC 2012). Unfortunately, the LCA report does not provide LCI information, and the LCI resulting from this study has been incorporated into the European reference Life-Cycle Database. The American Composite Manufacturers Association (ACMA) also commissioned a LCA study in 2012, which is estimated to be representative of more than half of the E-glass production volume in the U.S. (ACMA 2015). The outcome of this study is incorporated into the U.S. Life-cycle Inventory Database, and the report is not publicly available. Since detailed LCI data from neither study is publicly accessible, the two studies are not considered in this update.

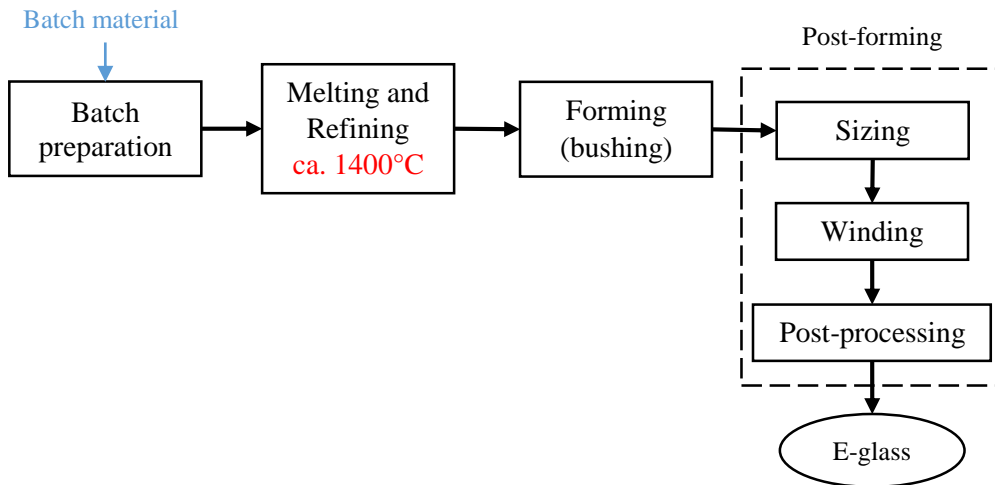


Figure 2. Schematic of E-glass production

3.1.1 Material Inputs of E-glass Production

The material requirement for the production of E-glass can also be back-calculated from its average composition. Unlike flat glass, the composition of E-glass is specified by the American Society for Testing and Materials (ASTM). According to the specification, E-glass for general applications should contain 52-62 wt% SiO_2 , 16-25 wt% CaO , 12-16 wt% Al_2O_3 , 0-10 wt% B_2O_3 , 0-5 wt% MgO , and 0-20 wt% others. Nonetheless, the exact E-glass compositions have evolved over the years as manufacturers continue to develop energy-efficient and environment-friendly compositions. In particular, to combat the particulate emissions associated with the boron and fluorine contents in the batch materials, new fluorine- and boron-free compositions were commercialized in the late 90s. However, the boron-free composition leads to increased energy consumption for the melting process and does not yet represent the majority of the E-glass market (Wallenberger 2010). Therefore, in this study, the borosilicate composition, which became the generic E-glass standard since 1951, and contains 54.5 wt% SiO_2 , 22.1 wt% CaO , 14.0 wt% Al_2O_3 , and 6.6 wt% B_2O_3 (Wallenberger 2010), is assumed for the calculation of raw material inputs. Kaolin is assumed to be the raw material for Al_2O_3 , and refined boron compounds are assumed to be the source for boron.

The water consumption for E-glass production is more significant than flat glass production. In addition to batch wetting, cooling, and cleaning, substantial amount of water is used for spraying and size preparation. Water added to size is estimated to be in the range of 50 gallons/ton, while water for spraying can be up to 720 gallons/ton (Scalet *et al* 2013). Due to the high temperature of the filaments coming out of the bushings, it is expected that part of the water spray in contact of the hot surface will evaporate, whereas the rest of the spray water can be collected and recycled. Total evaporative water loss for E-glass production is estimated to be 360-960 gallons/ton (Scalet *et al* 2013).

The LCI for boron and/or its compounds is nonexistent in 2014 GREET and is independently compiled in this study. Water and energy consumption pertaining to the production of 1 ton of refined B_2O_3 is obtained from the 2011 sustainability report of Rio Tinto's U.S. Borax Inc., which represents approximately half of the global demand for refined borates

(Rio Tinto 2012). Since the production process of refined B₂O₃ is similar to that of alumina, and the ore grades are also similar (USGS 2012), the fuel mix for the B₂O₃ production is approximated by that of alumina production.

Final glass fibers can contain 0.3-1.5 wt% of size (Woude and Van der Lawton 2010), and the environmental impacts associated with its use can be notable (PWC 2012). However, as its composition is unknown, it is not included in the LCI for E-glass production. Neither is the platinum-rhodium alloy used for the bushings, since it is fully recycled after the end of its lifetime.

3.1.2 Energy Inputs for E-glass Production

As with the case of flat glass production, energy consumptions for glass fiber manufacturing are also reported in several studies (Ruth *et al* 1997, DOE 2002, Rue *et al* 2007, Worrell *et al* 2008, Scalet *et al* 2013). It should be pointed out that some of the energy consumptions represent the production of both textile glass fiber and glass wool, as noted in Table 3. Again, the energy consumptions for melting and refining, together with the forming stages are obtained from Rue *et al* 2007, as they are more representative of current textile glass fiber production in the U.S. Energy requirements for the batch preparation and post-forming processes are based on the 2002 DOE report.

Table 3. Energy consumption for E-glass production (MMBtu/ton)

Processing stage	Ruth et al 1997	DOE 2002	Rue <i>et al</i> 2007	Worrell <i>et al</i> 2008	Scalet <i>et al</i> 2013
Batch preparation	1.15*	1.15*	0.68*	1.1*	---
Melting and refining	9.89*	5.6-10.5	6-7	5.6-10.5	6.02-15.48
Forming	7.24*	7.2*	1-2	2-5.5*	---
Post-forming	2.74*	3.28	1-2	3.3	---

*Data representing both textile glass fiber and glass wool production

3.1.3 Emissions from E-glass Production

The production of E-glass also emits CO₂ and SO_x from batch material decomposition, as well as thermal NO_x. In addition, the boron-containing batch material leads to more PM emissions than the float glass production. It is estimated that up to 15% of the added boron content can volatilize in the furnace and react with other species in the flue gas to form particles (Wallenberger 2010). Again, process emissions associated with E-glass production are calculated as the differences between the reported emissions in Scalet *et al* 2013 and the combustion emissions based on GREET emission factors.

3.2 Production of Glass Fiber Reinforced Composites (GFRP)

Glass fiber reinforced composites are produced by embedding glass fibers in a matrix. The matrix helps by keeping the reinforcing fibers together, distributing the load, and protecting the reinforcing systems. In contrast, the glass fibers improve the strength, stiffness and chemical resistance of the resultant composites (Ehrenstein and Kabelka 2000). Common matrices include polyesters, epoxies and vinyl esters, among which epoxies are the most widely used in advanced composite materials due to their potential to deliver the best strength performances at affordable prices (Ilschner *et al* 2000). The existing LCI of epoxy resin in 2014 GREET was obtained from the Plastics Europe database, and already represents the most recent available data. Therefore, it is used as is in this study.

The composites can be fabricated by combining the matrix with the reinforcing fibers through various processes. Sheet molding compounds (SMC), pre-impregnated fabrics (prepregs), and resin transfer molding (RTM) are the most relevant to the automotive industry (Ilschner *et al* 2000).

SMC combines chopped glass fiber rovings, epoxy resin and fillers in a continuous sheet, which is formed into complex shapes in the subsequent molding step. Common filler materials include calcium carbonates, dolomite, and china clay (Woude and Van der Lawton 2010). In this study, it is assumed to be china clay. Typical composite composition is 30% fiber, 30% resin,

and 40% filler (Orgéas and Dumont 2011). SMC can be used to produce automotive closure panels with class A surfaces (Woude and Van der Lawton 2010), as well as structural parts with complex shapes (Ilschner *et al* 2000).

Prepregs involve impregnating reinforced fabrics with partially cured matrix material followed by molding. They have a resin content of 30-40 wt% (Woude and Van der Lawton 2010), and can be used in high-load-bearing parts in automobiles (Ilschner *et al* 2000). In this study, the prepregs composition is assumed to be 40% resin and 60% fiber. Both SMC and prepregs facilitate automated production.

RTM is also known as resin/liquid injection molding. It features placement of the reinforced materials in a mold into which resin is subsequently injected to saturate the reinforcement. The glass fiber used can be continuous strand, cloth, woven rovings, or of other forms. Applications of RTM include truck and autobody components in the intermediate volume range (Bastone and Katz 2000). Since no composite composition for RTM is found in literature, the GFRP composition in 2014 GREET, 50% resin and 50% fiber, is assumed for RTM composites.

Energy consumption for the three composite fabrication processes are obtained from literature (Suzuki and Takahashi 2005, Das 2011) and are summarized in Table 4. It should be pointed out that the energy consumption for prepregs does not include that associated with atmosphere control, raw material storage and prepreg storage, which are not needed in the case of mass production (Suzuki and Takahashi 2005).

Table 4. Energy consumption for composites fabrication processes

Input	SMC	Prepregs	RTM
Energy consumption (MMBtu/ton)	3.0 ^a , 3.3 ^b	3.7 ^a	11.0 ^a

^a Suzuki and Takahashi 2005; ^b Das 2011

3.3 Summary

The updated LCI for E-glass production is presented in Table 5.

Table 5. LCI for E-glass production

Inputs	Batch preparation	Melting and refining	Forming	Post-forming
Natural gas (MMBtu/ton)	---	6.5	---	3.28
Electricity (MMBtu/ton)	1.15	---	2.00	---
Sand (ton/ton)	0.393	---	---	---
Limestone (ton/ton)	0.395	---	---	---
Kaolin (ton/ton)	0.327	---	---	---
Refined B ₂ O ₃ (ton/ton)	0.066	---	---	---
Water (gal/ton)	---	---	960	---
Emissions				
CO ₂ * (g/ton)	---	157,671	---	---
NO _x (g/ton)	---	2,217	---	---
PM (g/ton)	---	105	---	---
SO _x (g/ton)	---	679	---	---

* Based on stoichiometric calculation

4 CONCLUSIONS AND FUTURE WORK

This study updates the LCIs for the production of float glass, E-glass and GFRC in 2014 GREET. Raw materials and water inputs are added to the existing LCIs, while energy consumption and emission data are updated. The updated LCIs are supposed to better represent current production practices, characterized by considerably reduced energy consumption and more environmentally friendly operations.

Due to the high quality requirement of flat glass and textile glass fiber, post-consumer glass and external cullets (i.e., recycled glass) are not currently used in their production (Schmitz *et al* 2011), although in-house cullets are redirected to the furnace (Scalet *et al* 2013). Recycling of flat glass and textile glass fiber is therefore not considered in this study. As for the GFRC, a few technologies are considered as viable end-of-life options: mechanical recycling, pyrolysis, hydrolysis, and incineration with energy recovery (Duflou *et al* 2009). These technologies aim at recovering the energy embodied in the composites and can partially compensate the energy requirement for the composite production (Duflou *et al* 2012). However, as GREET adopts the recycled-content method when it comes to recycling, these end-of-life options are not examined in this study.

As aforementioned, the size used in the glass fiber production may result in considerable energy consumptions and greenhouse gas (GHG) emissions. Therefore, it should be revisited in future GREET updates if data of the size composition becomes available. In addition, the furnaces used in the glass industry need to be replaced every 5-15 years, as the refractory material deteriorates over time due to the high temperature (Rue *et al* 2007). Infrastructure for glass production is not included in this study due to data unavailability, but may be worth investigating in the future, since one furnace may cost more than \$20 million to build (Levine and Jamison 2001), which implies substantial material and energy consumptions.

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