Emerging energy efficiency and carbon dioxide emissions-reduction technologies for the glass industry

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Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for the Glass Industry

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Abstract
Glass production is a highly energy-intensive process. The ongoing increase in world glass demand means that this industry's energy use and CO_2 emissions will continue to grow without additional efforts for energy efficiency. There is significant incentive to develop, commercialize and adopt emerging energy efficiency and CO_2 emissions reduction technologies for glass production. Although prior studies have identified a wide range of energy efficiency technologies applicable to the glass industry that have already been commercialized, information is limited and decentralized regarding emerging (i.e., not yet commercialized) energy efficiency and low carbon technologies. This paper characterizes energy use in the glass industry and consolidates available information on 16 emerging glass production efficiency technologies, with the intent of providing a well-structured database of comparable information on these technologies for engineers, researchers, investors, glass companies, policymakers, students, and other interested parties. For each technology included, we provide information on the mechanism of achieving efficiency, case studies, challenges, energy savings, emissions reduction potential, other benefits, and commercialization status.

Contents

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1. Introduction

Glass production is a highly energy-intensive industrial process. Across various types of glass (container, flat, fiber, and special glass), the production process uses direct combustion of fossil fuels like natural gas and oil for energy, as well as electricity. Thus, glass production is a significant source of carbon dioxide (CO_2) emissions. According to the International Energy Agency (IEA), the container and flat glass industries (which combined account for 80% of glass production) emit over 60 megatons of CO_2 emissions per year (IEA 2007), which is more than the annual emissions from the country of Portugal. Demand for flat glass market (used in buildings and automobiles) is projected to have a compound annual growth rate of 5.5% through 2021 (Reportlinker 2017), and the global increase in glass consumption and production will drive significant growth in the industry's absolute energy use and CO_2 emissions.

Energy use accounts for about 15% of total glass production costs (Levine et al. 2003). Studies have documented the potential for the global glass industry to save energy by adopting commercially available energy efficiency technologies and measures (Worrell et al. 2008, Scalet et al. 2013). However, in view of the projected continuing increase in absolute glass production, future reductions (e.g., by 2025 or 2050) in absolute energy use and CO_2 emissions will require innovation beyond technologies that are available today. New developments will likely include different processes and management techniques. Deployment of these new technologies in the market will be critical for the industry's climate change mitigation strategies for the mid- and long-term. It should be noted that technology adoption in regions around the world is driven by economic viability, raw material availability, energy type used, energy cost, as well as regulatory regimes.

Information on emerging (i.e., not yet commercially available) energy efficiency and low-carbon technologies for the glass industry is highly limited and decentralized, a mix of private sector and academic information that is difficult for stakeholders across sectors to consider holistically. The glass industry is also very diverse in terms of size, type, location, and energy intensity of glass-producing enterprises. This review consolidates publicly available information on emerging technologies for the glass industry in a well-structured and comparable form to assist engineers, researchers, investors, glass companies, policy makers, and other interested parties.

The information presented for each technology was systematically collected from various publicly available sources. These include books, theses, journal papers, white papers, patents, conference proceedings, technical bulletins, web materials, reference documents on best available technologies and practices, and reports on industrial energy efficiency. We also assessed references from included studies to find other relevant research. To focus this review, we only sought literature that discussed non-commercialized technologies with direct impacts on energy efficiency in the glass production process. We did not consider studies that focused on energy efficiency technologies for other phases of the glass life cycle. In addition, this catalog focused on technologies for which there were multiple sources of information, thus excluding some promising emerging technologies that only had information available from the technology developer, for example. Although it covers the main emerging energy efficiency technologies for the glass industry, the list of emerging technologies addressed is not exhaustive.

The paper begins with an overview of the glass production process. Next, the paper uses a uniform structure to present reviewed information about each of the 10 technologies covered. First, we describe the technology, including background, barriers, and case studies if available. Next, we present the energy, environmental, and other benefits of the technology, in that order and if available. For some technologies, we include an illustrative diagram or picture. Finally, we identify the commercialization status of each technology as well as resources for further information. The commercialization status of each technology is as of the writing of this paper and uses the following categories:

- Research stage: The technology has been studied, but no prototype has been developed.
- Development stage: The technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: The technology is being tested at an industrial-scale pilot plant.
- Demonstration stage: The technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven.
- Commercial with very low adoption rate stage: The technology is proven and is being commercialized but has a very small market share.

Table 1 lists the 16 technologies covered in this paper, the section of the paper in which each technology is discussed, and the technology's commercialization status. Table 1 also includes our assessment of each technology's Technology Readiness Level (TRL) according to Department of Energy guidelines. The TRL is a scale of technology maturity from 1 to 9, with 1 being the least mature technology (basic principles observed and reported) and 9 being the most mature (technology proven through successful operations). This is contrast to commercialization status, which assesses economic progress.

Table 1. Emerging energy efficiency and CO_2 emissions reduction technologies for the glass industry

Paper Section/Technology Name	Commercialization status	TRL
3.1. Emerging Technologies in Batch Preparation		
3.1.1. Selective Batching	Development stage	6
3.1.2. Laser-Induced Breakdown Spectroscopy for Improved Control of Glass Feedstock	Pilot stage	7
3.2. Batch and Cullet Preheating		
3.2.1. Raining Bed Batch and Cullet Preheating	Development stage	7
3.2.2. E-Batch Preheating Technology	Pilot stage	8
3.3. Emerging Technologies for Glass Melting		

Paper Section/Technology Name	Commercialization status	TRL
3.3.1. Oscillating Combustion	Pilot stage	7
3.3.2. Segmented Melter	Research stage	3
3.3.3. Plasma Melter	Pilot stage	6
3.3.4. Submerged Combustion Melting	Development stage	4
3.3.5. In-flight Melter	Research stage	4
3.3.6. Porous Burners	Development stage	4
3.3.7. Glas Flox® Flameless Burner	Pilot stage	7
3.3.8. Microwave Heating	Research stage	2
3.4. Process Control Technologies		
3.4.1. Glass Furnace Model: Glass Melting Simulation Software	Commercial with low adoption stage	9
3.4.2. Image-Based Control of Glass Melting Furnaces	Pilot stage	7
3.5. Conditioning and Forming		
3.5.1. Oxy-fuel Fired Forehearths	Pilot stage	5
3.5.2. Single Stage Forming	Research stage	3

The purpose of this paper is solely informational. Many emerging technologies are proprietary and/or the manufacturers who are developing a new technology are the primary sources of information about it. Because the nature of emerging technologies is continual and often rapid change, the information presented in this paper is also subject to change.

2. Brief Description of Glass Production Processes and Energy Use

Across the various types of glass, the production process shares the same general steps. The production process begins with procurement of the source material for the glass, which can be either raw material such as silica sand or ground-up waste glass (called cullet). The first step in glass production is the preparation of a mix of ingredients in a batch for the melting furnace. The glass batch contains formers, fluxes, stabilizers, and sometimes colorants, each of which can affect the properties of the final glass product. Materials are ground to their proper grain size, weighed, and then blended. Batch preparation uses energy in the form of electricity for transport, mixing, and agglomeration of materials. The batch mixer accounts for the greatest share of electricity use in this process step, while batch preparation overall is about 4% of a glass plant's total energy demand (Worrell 2008).

Next, in the melting stage, the prepared batch is fed into the furnace, where it is melted and withdrawn at a controlled rate. The melting step represents over half of energy use in glass production (IEA 2007). Most glass producers use combustion heating, direct electrical heating, or both to melt the glass batch material. Combustion heating often uses natural gas or fuel oil. Commercialized efficiency technologies aim to reduce NOx emissions from combustion in air and to recover waste heat through various regenerative and recuperative systems.

After being melted and refined, the molten glass enters the forehearth for conditioning. The forehearth delivers glass at a carefully maintained temperature and temperature distribution to the forming equipment. Forming equipment varies based on the final glass product being produced. The glass can be formed through a continuous shaping process for float glass or fiberglass, or it can be delivered in portions (“gobs”) to make container glass. The conditioning and forming steps can use between one eighth and one third the energy used in the glass production process, depending on the type of glass. Natural gas is used for heating, while electricity is used for conveyors, fans, and mechanical pressing (Worrell 2008).

Further finishing procedures may be performed depending on glass type and intended use.

3. Emerging Technologies for Energy Efficiency and CO_2 Emissions Reduction in the Glass Industry

In this section, emerging energy efficiency and emissions reduction technologies are presented, organized by production phase.

3.1. Emerging Technologies in Batch Preparation

Batch preparation includes mixing, weighing, and blending the raw materials that will be used to produce glass. Batch preparation can determine the final quality of the glass as well as the melting time when the raw material goes into the furnace, which is a major determinant of energy use.

3.1.1. Selective Batching

Description: Batches can become segregated when alkali and alkaline-earth carbonates react preferentially, leading to increased melting time and thus more energy use. Selective batching is a method of increasing melting efficiency by controlling the reaction paths of batches as they melt, preventing early formation and segregation of low-viscosity liquids. Selective batching can reduce melting time by improving control over reaction pathways - decreasing the alkali and alkaline-earth reactions, and promoting desired reactions between the fluxes and quartz earlier.

In one proposed method of selective batching, the batch raw materials are separated into first and second portions with different compositions and reaction paths. Additional materials are added to prepare mixtures for the melter. The first composition has a first melting temperature, while the second composition has a second melting temperature. The first liquid fluxes the second composition to yield a molten glass composition (Carty 2013).

Selective batching may not be suitable for large-scale glass manufacturing. Research has focused on spray drying to pre-mix raw materials, which must be finely ground. This has led to initial tests being focused on glass fibers (Worrell 2008).

Energy/Environment/Cost/Other Benefits:

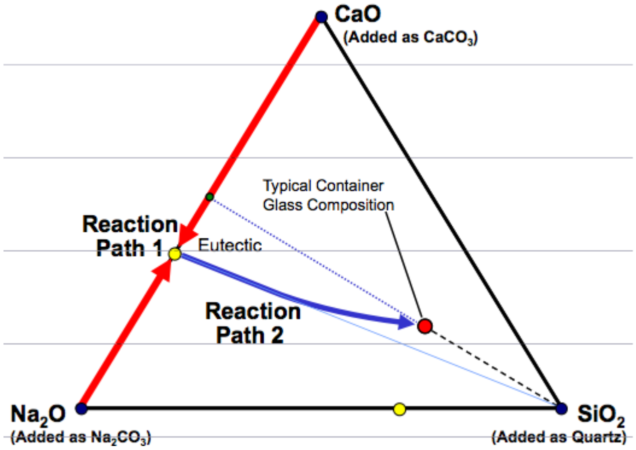
- 50% shorter melting time
- Fuel savings of 20-33% (Carty and Sinton 2004)

Commercial Status: Development Stage
TRL: 6

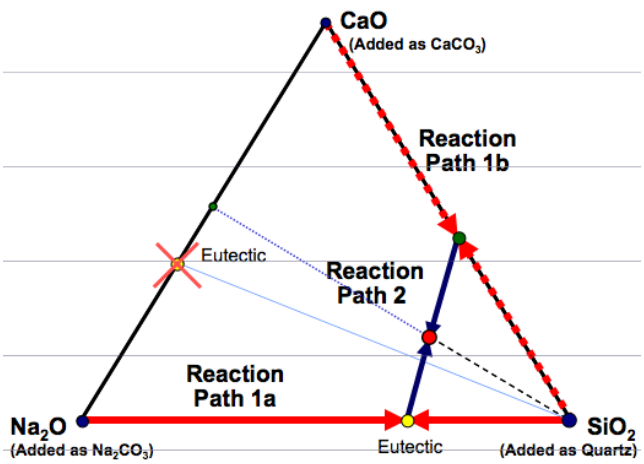
References: Carty 2013, Worrell 2008, Carty and Sinton 2004, Carty et al. 2011

Block Diagram:

Typical Reaction Path:



Forced Reaction Path via Selective Batching:



Source: Carty et al. 2011

3.1.2. Laser-Induced Breakdown Spectroscopy for Improved Control of Glass Feedstocks

Description: Laser-induced breakdown spectroscopy (LIBS) has been used to improve process control in other industries, but is particularly well-suited to increase the yield and quality of glass. While LIBS is a commercialized technology for other applications, its use for in situ measurement of industrial-scale manufacturing has yet to be proven. LIBS probes can measure the chemical makeup of glass feedstock in real time, detecting potential contaminants and preventing low-quality mixtures from entering the furnace. It can also detect colors and assess both granular and larger materials in a batch. Preventing defective glass from being produced can save manufacturers money and improve the quality of their glass. In addition, LIBS can greatly improve the glass recycling process, reducing recycling time, chemical additives, and energy used (Matiaske et al. 2011).

Over a long period of time, LIBS data can help factory operators identify the relationship between batch properties and operating outcomes such as particulate matter emissions and crown corrosion. By providing high-quality data on batch characteristics over time, LIBS can enable operators to adjust conditions to optimize their product, reducing emissions and extending furnace life (U.S. DOE ITP 2003).

Challenges for LIBS include signal variability and the need for high-speed analysis of LIBS data to correct problems in real-time (U.S. DOE ITP 2003). Spectrometer technologies in LIBS systems require further improvements (Lal et al. 2005).

The Federal Institute for Materials Research and Testing in Germany has assessed a double-pulse LIBS system for glass with the goal of using the results for industrial applications (Matiaske et al. 2011). An experimental LIBS system was installed at a fiberglass plant in Chester, South Carolina in 2004 (De Saro et al. 2005).

Energy/Environment/Cost/Other Benefits:

- A 20% reduction in product defects, which could save the U.S. glass industry $220 - $440 million per year
- Energy savings of around 54,000 GJ or $358,000 per year for a single-furnace glass factory producing 250 tons per day (De Saro et al. 2005)

Commercial Status: Pilot Stage

TRL: 7

References: Matiaske et al. 2011, Lal et al. 2005, De Saro et al. 2005, U.S. DOE ITP 2003

3.2. Batch and Cullet Preheating

Preheating batch and cullet with furnace exhaust gases can improve furnace energy efficiency by evaporating moisture in the batch, reducing the heat required to reach melting temperature, and lowering the overall furnace peak temperature. Many technologies have been explored, including some that were installed on a commercial scale. However, preheating technologies have not achieved widespread use because of ongoing issues with operational reliability and cost effectiveness (Alexander 2009). The following technologies are a selection of the most-documented emerging batch and cullet preheating technologies.

3.2.1. Raining Bed Batch and Cullet Preheater

Description: The raining bed batch and cullet preheater technology uses a heat exchanger to re-capture heat energy from hot combustion gases. The ‘raining bed’ is so named because the batch and cullet are fed through the preheater and then fall through the heat exchanger, capturing heat from direct contact with the rising flue gases. The heat exchange process can preheat the batch and cullet to over 500° C (Worrell 2008), lowering the demand for combustion energy.

The first company to develop this concept was Tecogen. The system was then laboratory tested by a number of other companies. In 1999, the Department of Energy and Thermo-Power tested several pilot units. A major challenge to raining bed batch and cullet preheaters is that they are capital-intensive and may even require equipment similar in size to the melter (Rue et al. 2007).

Energy/Environment/Cost/Other Benefits:

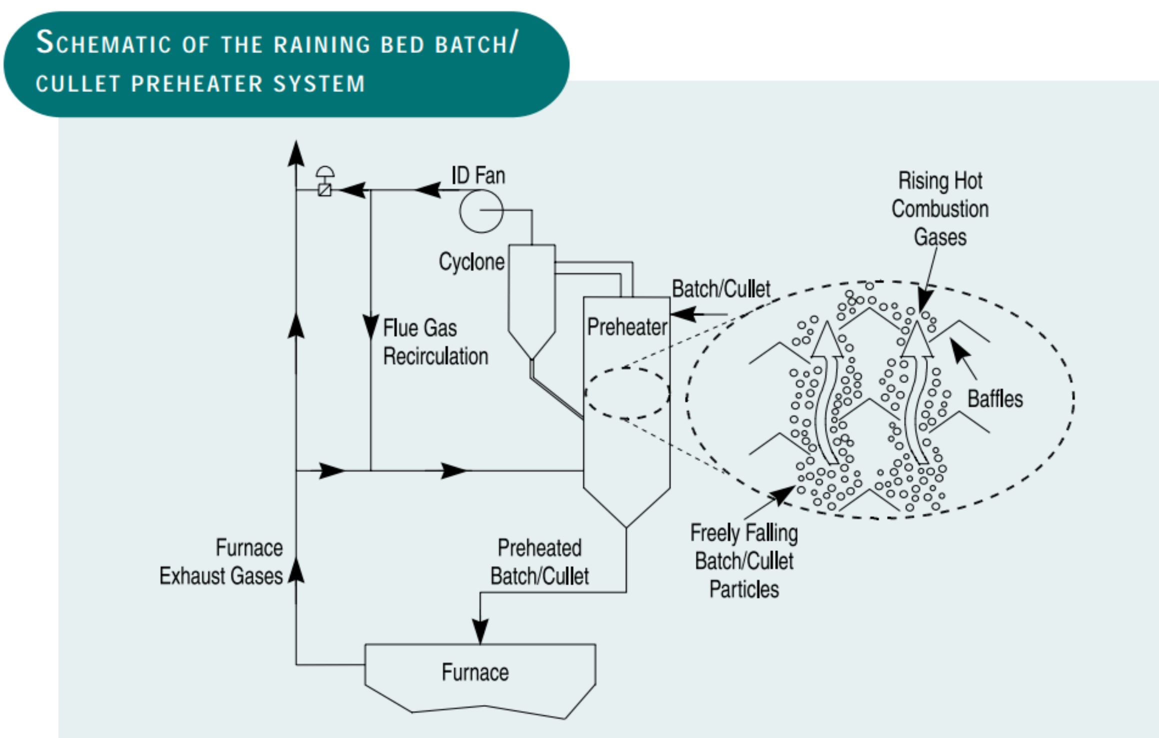
- Recovery of 527 MJ per ton of glass produced via this process
- 25% reduction in fuel and oxygen in oxyfuel glass furnaces
- Equipment payback period of less than four years
- Reduction of clogging and plugging problems sometimes associated with batch preheating due to the free-falling material (Worrell 2008)

Commercial Status: Development stage

TRL: 7

References: Worrell 2008, Rue et al. 2007, OIT 1999

Block Diagram:



Schematic of the raining bed batch and cullet preheater system (OIT 1999)

3.2.2. E-Batch Preheating Technology

Description: The electrostatic batch preheating technology, or E-Batch, is another batch and cullet preheating technology designed to recapture heat from exhaust gases. An E-Batch module is installed, which uses a discharge feeder to transfer preheated material to the furnace in a continuous flow. Exhaust gases preheat this material through tubes at the bottom of the module. Since the contact between the gases and the batch material can cause reactions that increase the amount of particulate matter in the gases, the E-Batch technology also uses a patented electrostatic mechanism to precipitate particulates in the furnace exhaust gases onto the batch surface, preventing them from escaping as emissions. E-Batch is also designed to integrate with oxy-fuel fired furnaces (GMIC et al. 2004).

The E-Batch technology was developed and patented by BOC Gases in 2001 (Alexander 2001). A unit was tested in a laboratory and then piloted at the plant level, with positive results. Potential problems include dust buildup on the surfaces of the E-Batch tubes and electrodes, and condensation from moisture in the exhaust gases, although these did not reduce performance in the laboratory and pilot tests (Alexander 2009). In fact, there are several patents that propose a variation on this technology that combine cullet preheating and electrostatic collection of particulate matter.

Energy/Environment/Cost/Other Benefits:

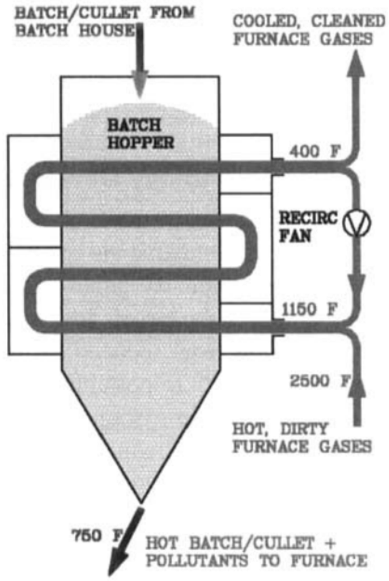
- 15-25% reduction in furnace energy requirements (Alexander 2009)
- Significant reduction of particulate matter emissions
- Ability to handle any mixture ratio of batch and cullet

Commercial Status: Pilot Stage

TRL: 8

References: GMIC et al. 2004, Alexander 2001, Alexander 2009

Block Diagram:



3.3. Emerging Technologies for Glass Melting

Melting is by the far the most energy-intensive phase of glass production, and thus represents the greatest opportunity for implementing energy efficient technologies. Existing energy efficiency technologies for melting include waste-heat recovery systems, improvement of insulating materials, and the use of oxygen to improve the efficiency of combustion in the furnace (Worrell 2008). It should be noted that switching to electrical melting can have emissions benefits if the electricity comes from low-emissions sources, but this is not discussed in the following sections because emissions benefits of fuel-switching are not determined at the plant level.

3.3.1. Oscillating Combustion

Description: Oscillating combustion can be applied for furnace efficiency improvement in a number of industries, including the glass industry. Oscillating combustion refers to forcing oscillations in the fuel flow rate to a furnace, creating successive fuel-rich and fuel-lean areas in the furnace. Fuel-rich areas increase the heat applied to the batch materials, while fuel-lean areas reduce the production of NO_x and undesirable byproducts of the reaction by operating closer to the ideal stoichiometric ratio. Overall, oscillating combustion can reduce the peak temperature of the furnace, saving energy.

Oscillating combustion technologies can be retrofitted onto existing many different types of glass furnaces by installing an oscillating valve on the fuel line to each furnace, and control equipment for groups of valves (Worrell 2008). This simple retrofit has the added benefit of not requiring additional modification of the furnace, reducing retrofit costs.

The Gas Technology Institute (GTI) has used oscillating combustion technologies to test applications in both glass and steel production (Govardhan and Rao 2010). Pilot projects have also been carried out on stack annealing and fiberglass melting furnaces (Worrell 2008).

Energy/Environment/Cost/Other Benefits:

- Reported fuels savings range from 2% to 27%, with an overall efficiency improvement of up to 6% and reduction in specific energy consumption of 16% to 32% (Govardhan and Rao 2010)
- Reduced NO_x emissions of 30% to 50% (Worrell 2008)
- Reduced melting time

Commercial Status: Pilot stage

TRL: 7

References: Govardhan and Rao 2010, Worrell 2008, Wagner 2004

Block Diagram:

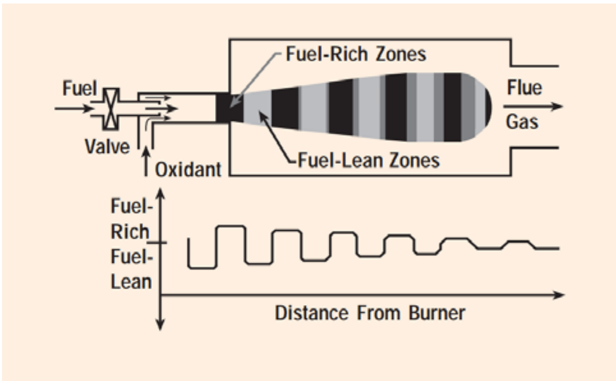


Diagram of an oscillating combustion technology with fuel-rich and fuel-lean zones (Wagner 2004)

3.3.2. Segmented Melter

Description: Segmented melters separate the melting processes for the main materials in glass, the batch and the cullet, which have different melting temperatures and residence times. Segmentation of the melting process allows optimization of each stage, since each stage requires special conditions. In a segmented melter, the batch is melted first in an electric melter at a temperature of around 1400°C (Karlsruhe Institute of Technology 2004). After adding the cullet, which has a lower melting temperature, the mixture enters a second oxy-fueled melting chamber with a lower temperature. The lower temperature and overall shorter residence time in the melter reduces emissions and increases efficiency.

Drawbacks to segmented melters include high maintenance requirements and costs, meaning that despite several prototype designs, segmented melters have not been commercialized yet (Worrell 2008).

Energy/Environment/Cost/Other Benefits:

- A lower residence time can lead to increased yield and lower thermal losses (a 25% improvement in thermal efficiency) (KIT 2004)
- Additional benefits include a lower tank volume, saving on material costs, and the ability to do local repairs in each segment (GMIC et al. 2004)

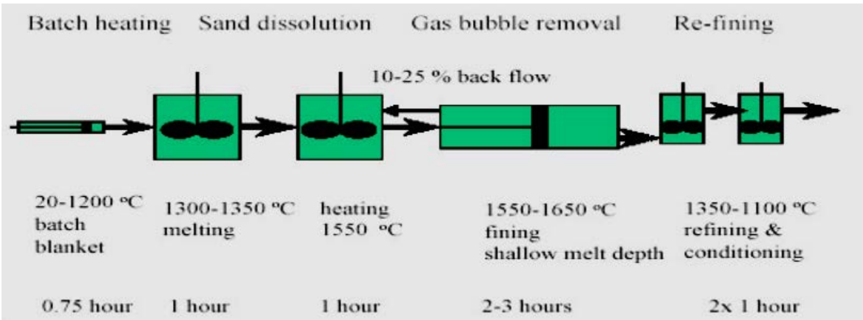
- If the batch melting uses an electric furnace, on-site emissions can be eliminated in the high-temperature stage of melting
- An oxy-fuel burner in the cullet melting phase would reduce NO_x emissions (KIT 2004)

Commercial Status: Research stage

TRL: 3

References: KIT 2004, Worrell 2008, GMIC et al. 2004

Block Diagram:



Arrangement of segmented melter sections with temperature levels and residence times (Source: KIT 2004)

3.3.3. Plasma Melter

Description: Thermal plasmas are important for material processing because they have high enthalpy and reactivity and can easily generate high temperatures. Plasma arc melting of glass has an energy density 2.5 times higher than conventional glass melting, allowing melting to occur more rapidly and efficiently (GMIC et al. 2004). Plasma electrodes allow plasma (in this case, ionized argon gas) to circulate and heat the batch via an electrical current. Plasma melters are well-suited to glass batch processes that require high melting temperatures and/or low production volume (Verheijen 2008). Plasma melters are also very flexible, and could be used to manufacture several different types of glass in a few hours. Cost is a challenge for plasma melters, as the argon gas can be expensive (Verheijen 2008).

Triple-torch plasma melters were first explored in the U.K. in the 1990s, though never commercialized (GMIC et al. 2004). The U.S. Department of Energy has also supported research into the Plasmelt process, including a pilot melter created by Plasmelt Glass Technologies, LLC (Prokhorenko 2008).

Energy/Environment/Cost/Other Benefits:

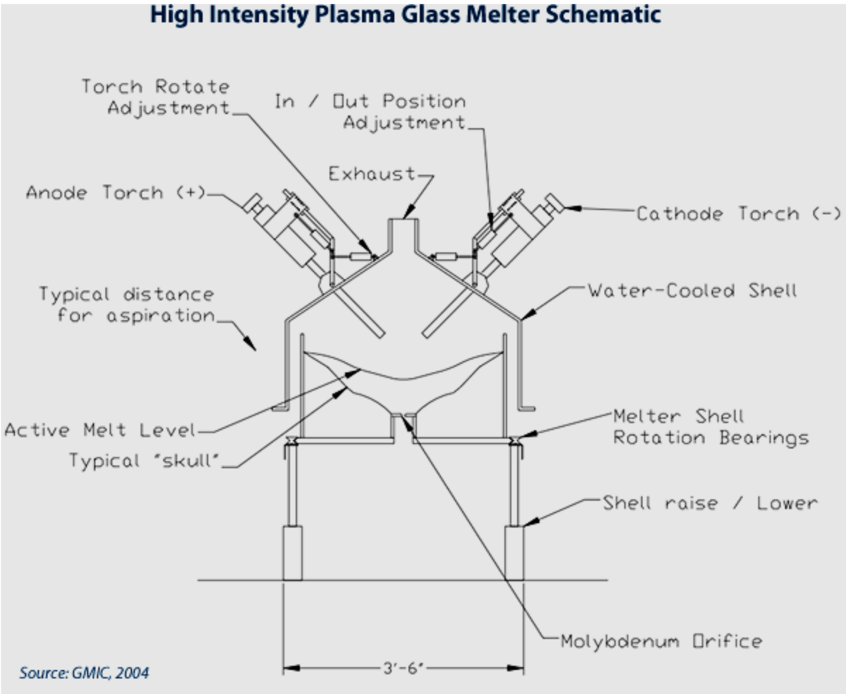
- Improvement in energy intensity of 50%-70% (IIP 2013a) (GMIC et al. 2004)
- Estimated system cost of $500,000 - $700,000 for a 500 lb/hour facility (IIP 2013a)
- More flexible, modular melting for small-scale manufacturers with multiple product types

Commercial Status: Pilot stage

TRL: 6

References: Worrell et al. 2008, GMIC et al. 2004, Verheijen 2008, Prokhorenko 2008, IIP 2013

Block Diagram:



3.3.4. Submerged Combustion Melting (SCM)

Description: Submerged combustion melting (SCM) fires fuel and oxidants directly into and under the surface of the melting mixture in a furnace. In SCMs, the burners are on the bottom of the glass furnace. As the combustion gases bubble through the melt, they maximize heat transfer, convective stirring, and particle dissolution. This increases the melting rate and reduces the residence time of the melt in the tank, saving energy (Scalet et al. 2013). SCMs also can handle a wider range of particle sizes, potentially reducing material costs.

One drawback of SCMs is that they can only be used with natural gas. While natural gas is less carbon-intensive than fuels like coal, it is still less clean than renewable-generated electricity. Other challenges include excessive noise, vibration, and wear (GMIC et al. 2004).

SCMs have been commercialized in the mineral wool industry, but are still at the pilot stage for glass manufacturing. Early trials began in the 1960s and 1970s in the United States, but have yet to be commercialized. Currently, the Glass Technology Institute and a consortium of companies are researching next-generation melting systems, including SCMs.

Energy/Environment/Cost/Other Benefits:

- Capital costs could be reduced by 55%-80% (IIP 2013, Rue and Brown 2011)

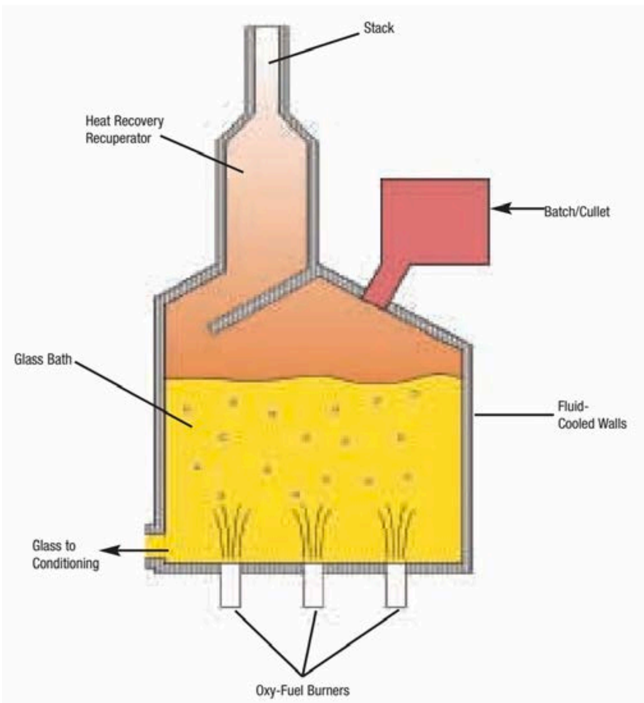
- Energy savings are estimated at 5%-20% compared to a state-of-the-art oxy-fuel furnace. The range is determined by heat recovery from the furnace wall. (Worrell et al. 2008)
- Fast start-up and shut-down times, safer operation and repairs due to cooler walls
- Reduction of NO_X emissions is expected due to quenching of flames in the melt (Scalet et al. 2013).

Commercial Status: Development stage

TRL: 4

References: Scalet et al. 2013, GMIC et al. 2004, Rue and Brown 2011, IIP 2013, Worrell et al. 2008, Purnode 2008

Block Diagram:



Schematic of a submerged combustion melter (Purnode 2008)

3.3.5. In-flight Melter

Description: The in-flight glass melter disperses granulated raw material in a melter such that the raw material is in full contact with a flame, allowing rapid heat transfer. Byproduct gases are removed when the raw material is injected, preventing bubbles and allowing the melting to occur more quickly. The in-flight melter can also handle different heating sources, including thermal plasma, a 12-phase AC arc, and an oxygen burner.

In-flight melting has been investigated extensively by at the Tokyo Institute of Technology at a laboratory scale, with promising results especially with in-flight melting combined with a thermal plasma (Yao et al. 2008).

Energy/Environment/Cost/Other Benefits:

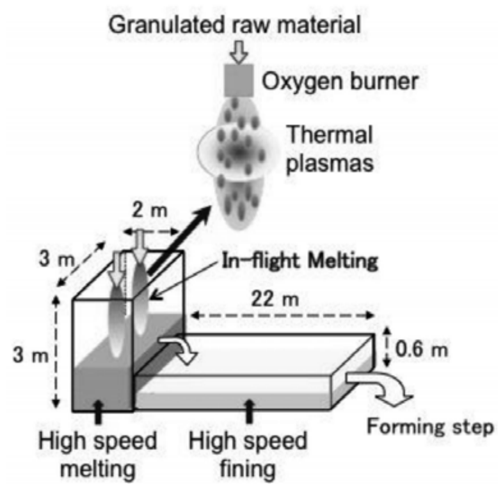
- Faster melting time, saving energy and increasing yield

Commercial Status: Research stage

TRL: 4

References: Yao et al. 2008, Watanabe et al. 2010

Block Diagram:



Schematic of an in-flight melter (Watanabe et al. 2010)

3.3.6. Porous Burners

Description: Porous burners have been commercialized for a number of industrial and heating processes that take place at low and medium temperatures. Current research is under way to investigate high temperature applications of porous burners, including for glass production. Porous burners allow combustion to take place within a porous medium, such as a ceramic matrix with large pores where reactions take place, and smaller pores for preheating materials (Reusse and Trimis 2005). Porous burners allow better control of the reaction process, and are less sensitive to fluctuations in fuel quality, saving energy (IIP 2013b). For glass production, porous burners would use natural gas as the combustion fuel.

A consortium of institutes in Germany is researching ceramic materials for porous burners (Reusse and Trimis 2005). Developing materials that can withstand high temperature gradients is the main challenge of applying porous burners to high temperature processes.

Energy/Environment/Cost/Other Benefits:

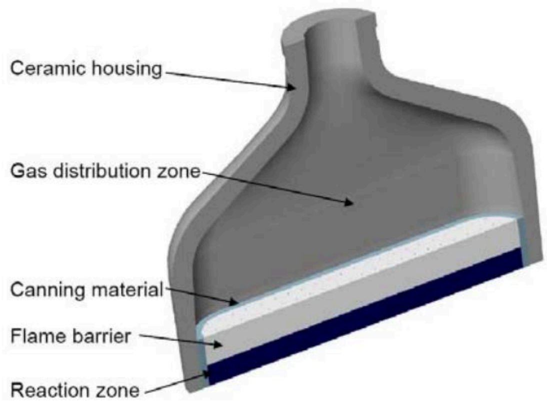
- Improved controllability, leading to energy savings, lower emissions, and higher quality glass

Commercial Status: Development stage

TRL: 4

References: IIP 2013b, Reusse and Trimis 2005

Block Diagram:



Schematic drawing of the burner construction (Reusse and Trimis 2005)

3.3.7. Glas Flox® Flameless Burner

Description: Glas Flox® burners are a German technology. 'Flox' refers to a flameless burner where the combustion gas and air go into the combustion chamber at a high flow rate. Mixing is delayed, preventing a large, visible flame from forming. The combustion chamber can achieve very high and homogenous temperatures. This leads to improved energy transfer to the melting glass. The reduced flame temperatures at the burner nozzles also reduce generation of thermal NOx, an undesired byproduct.

In a pilot system at the Gaswarme-Institute in Germany, the Glas Flox burners also used exhaust gas heat to preheat the combustion air, further improving efficiency (BINE Informationsdienst 2016).

Challenges to flameless burners include lack of familiarity on the part of the glass industry due to visible differences from conventional burners, which have a visible flame whose strength is perceived to be associated with production rates. Another concern is the high flow rate in the flameless burners, which could perturb the raw materials.

Energy/Environment/Cost/Other Benefits:

- Lower specific energy consumption and reduced CO_2 emissions
- 50% reduction in NOx emissions compared to conventional burners (Scalet et al. 2013)

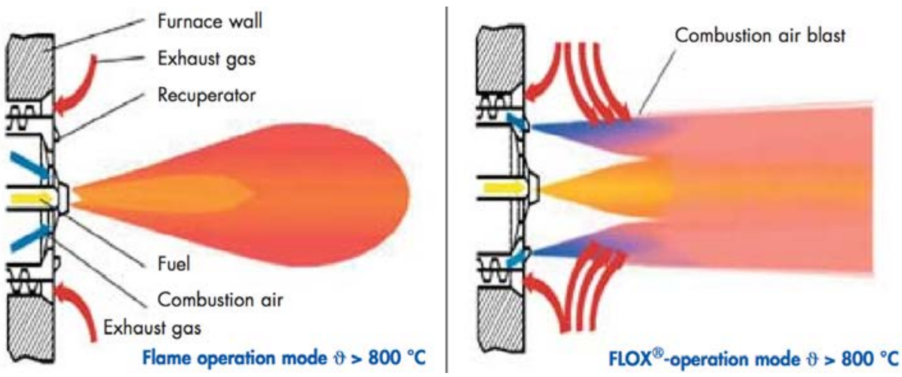
- Ability to be implemented as a retrofit to existing facilities

Commercial Status: Pilot stage

TRL: 7

References: Scalet et al. 2013, BINE Informationsdienst 2016

Block Diagram:



A figure comparing the conventional and FLOX burners (BINE Informationsdienst 2016)

3.3.8. Microwave Heating

Description: Microwave heating is a low-temperature alternative to conventional glass furnaces. Microwave melting of materials has achieved success in the laboratory for small-scale applications to ceramics, composites, and metals (of course, microwave heating has achieved widespread commercial success for food preparation). It can be used to produce a wide range of glasses, including different finishes (Mimoso et al. 2017). Microwave heating is far more rapid than the melting that occurs in a conventional glass furnace due to its higher heating rate. In addition, microwave heating can reduce direct emissions by using electricity as the source of energy, unlike conventional furnaces. A major challenge to microwave heating is controlling the temperature distribution in heated glass, which is less uniform when heating via microwave (Kharissova et al. 2010).

Researchers are working on a simulation of microwave heating to predict heat transfer patterns, and how to design an industrial microwave oven. Scientists have used numerical models to study the physics of microwave hearing applied to biomass, water, and alumina. Emerging research on operations control can help improve efficiency of glass microwave heating. Mimoso et al. 2017 developed a numerical methodology implemented using COMSOL software and automated controls to optimize energy efficiency in microwave heating. Since microwave heating is an emerging technology itself, this control method faces challenges in obtaining adequate data for validation of the software.

Energy/Environment/Cost/Other Benefits:

- Industrial microwave ovens could decrease glass melting time by an order of magnitude
- Half the energy intensity of conventional furnaces (Mimoso et al. 2017)

Commercial Status: Research stage

TRL: 2

References: Mimoso et al. 2017, Kharissova et al. 2010

Block Diagram:

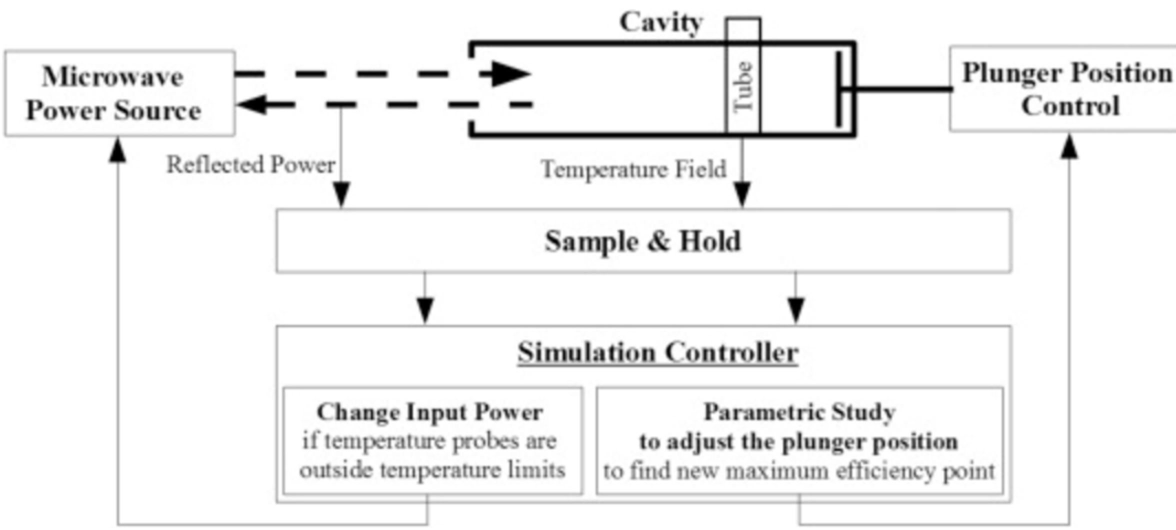


Diagram showing how the operations controls interact with the microwave glass heater

3.4. Process Control Technologies

Process control technologies can help optimize the melting process. These technologies include data-gathering devices within the glass production system, as well as models and software. There is a substantial literature on improving models of the glass-melting process, however, for this report, we have focused on emerging process control products, such as software, that can be commercialized and widely deployed for glass manufacturers.

3.4.1. Glass Furnace Model: Glass Melting Simulation Software

Description: Argonne National Laboratory, in collaboration with several partners, has developed a software that simulates a virtual furnace in order to analyze furnaces or improve new furnace designs. The software models radiation heat transfer in order to estimate gas flow and melt flow within the entire furnace. Users can specify burners and exhaust vents in the virtual furnace to match their actual furnace designs in user-friendly software interface. The software can help furnace operators reduce energy use and emissions without have to go through costly physical testing, instead specifying optimal operating windows and furnace designs (ANL 2017). Several versions of the Glass Furnace Model have been released, with commercial licenses available for purchase. However, it has not been as widely adopted as intended, possibly due to issues with the user interface in earlier versions (Lottes and Petrick 2007).

Energy/Environment/Cost/Other Benefits:

- Improve furnace efficiency by 5%
- Save costs through virtual simulation

Commercial Status: Commercialized with low adoption

TRL: 9

References: Lottes and Petrick 2007, Argonne National Laboratory 2017

3.4.2. Image-Based Control of Glass Melting Furnaces

Description: Images of the melting glass surface are often analyzed manually for quality control. Some automated imaging systems have been commercially developed, such as the SIGLAS optical melt control system by Siemens. These optical control systems use automated video analysis to control energy transfer in the furnace, improving efficiency by maintaining optimal temperatures for batch melting.

These existing systems can be improved by adding automatic analysis of melting symmetry, which refers to the symmetry of temperature distribution and the batch blanket. A method proposed by Rotter 2013 measures symmetry through image analysis using temperature asymmetry indicators implemented with computational algorithms. This method can identify the cause of asymmetry, allowing correction. The system is being tested at three glass factories in Poland.

Energy/Environment/Cost/Other Benefits:

- Can reduce operating costs by saving energy
- Reduced NOx emissions through improved process control
- The already-commercialized Siemens SIGLAS system is estimated to reduce energy use by 2% to 8%, providing a potential rough estimate of how much other process control technologies could save (Siemens 2006)

Commercial Status: Pilot stage

TRL: 7

References: Rotter 2013, Siemens 2006

3.5. Conditioning and Forming

Conditioning and forming determine the final shape and quality of the glass product. Different types of glass require different amounts of energy in the forming process; for example, fiberglass requires more primary energy to produce.

3.5.1. Oxy-fuel Fired Forehearths

Description: More efficient oxy-fuel combustion technology has already been successfully commercialized in glass furnaces. The oxy-fuel technology can also be applied to forehearths for fiberglass production. Conventional forehearths are long, narrow channels with air/fuel burners that require energy to heat the air to combustion temperature. Oxy-fuel burners for the forehearth can eliminate the need for this additional heat energy. In addition, oxy-fuel burners improve heat transfer through hotter flames. Owens Corning, with support from the U.S. Department of Energy, began research on oxy-fuel fired forehearths for fiberglass production in the early 2000’s (Jian and Mighton 2007).

Some challenges to implementing oxy-fuel burners on forehearths include potential overheating due to the hotter oxy-fuel flame and the high capital cost of installation.

Energy/Environment/Cost/Other Benefits:

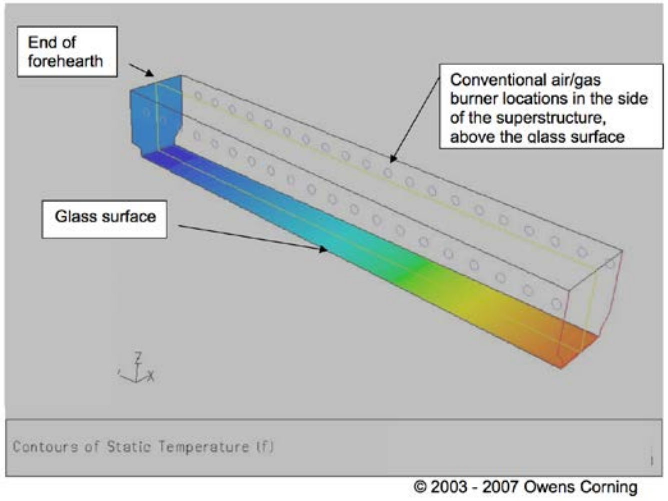
- Reduces gas consumption (around 64% reduction for the Owens Corning pilot) (Jian and Mighton 2007)
- Eliminates inert nitrogen in the original air/fuel mixture, potentially reducing NOx emissions
- One oxy-fuel burner can replace multiple old burners on a forehearth, potentially saving materials, labor costs, etc.
- Potential payback time of three years, depending on the price of natural gas (Jian and Mighton 2007)

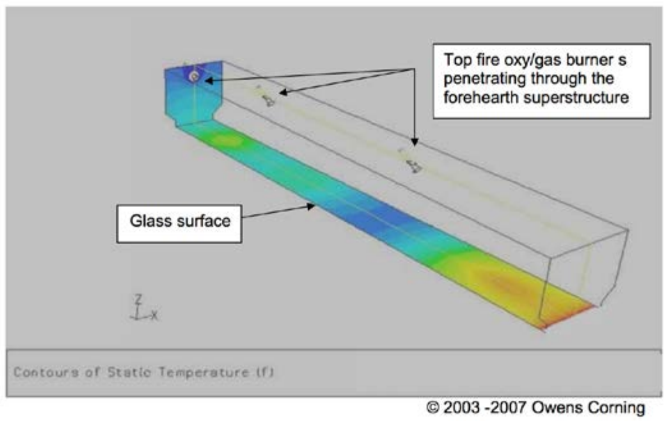
Commercial status: Development stage

TRL: 5

References: Jian and Mighton 2007

Block Diagram:





Two figures comparing a conventional forehearth (top) with multiple burner locations and an oxy-fuel fired forehearth (bottom) (Jian and Mighton 2007)

3.5.2. Single-Stage Forming

Description: Container glass is usually formed in a two-stage process. In the first stage, molten glass is formed into an intermediate product called a parison. Then, the parison is blown into its final shape. Container glass formed in two steps is thick and durable, but emerging single-stage forming technologies could contribute to glass lightweighting by preserving glass integrity while saving raw material and energy. Single-stage forming requires careful management of the temperature distribution in the gob, since there is no second stage to correct mistakes. One single-stage forming technology invented in Germany combines homogeneous forming temperatures with an aluminum tri-chloride lubricant that strengthens the surface of the glass (VDMA 2011). Another technology to aid single-stage forming is a porous plunger, which would allow the molten glass to be blown inside a single forming mould (Eustice 2008). Single-stage forming machinery has not yet been developed for pilot study.

Energy/Environment/Cost/Other Benefits:

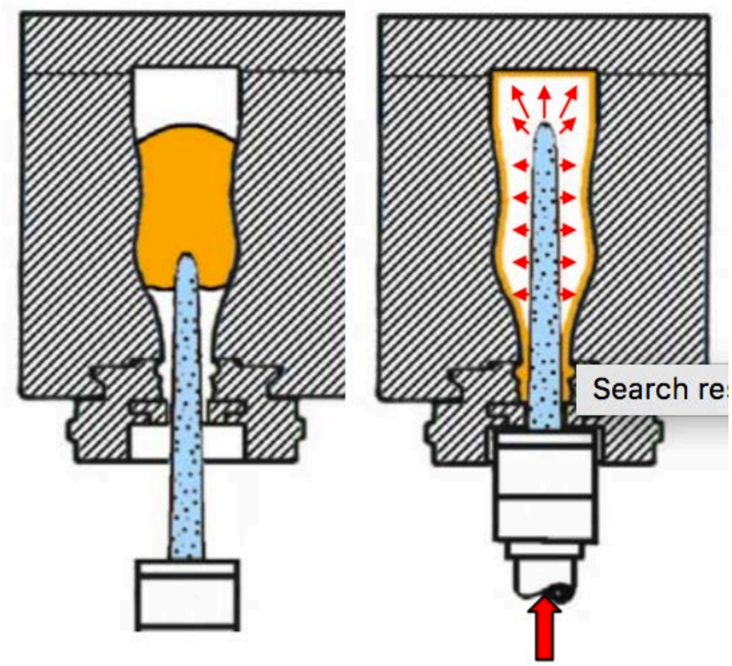
- 15% cost savings (VDMA 2011)
- Less raw material and energy used

Commercial Status: Research stage

TRL: 3

References: VDMA 2011, Eustice 2008

Block Diagram:



Single stage pressing and blowing with a porous plunger (Eustice 2008)

4. Conclusion

This paper describes 16 emerging energy efficiency and CO_2 emissions reduction technologies or processes for the glass industry. The information presented for each technology was collected from various publicly available sources. It is likely that no single technology will be the best or only solution for a more energy efficient glass industry – instead, a portfolio of commercial and emerging technologies should be deployed to address the increasing energy use and CO_2 emissions of the glass industry. The following table summarizes point estimates (in varying units) for energy and cost savings for the technologies that had such information.

Table 2: Energy and cost savings estimates for technologies

Paper Section/Technology Name	Energy Savings Estimate	Cost Savings Estimate
3.1. Emerging Technologies in Batch Preparation		
3.1.1. Selective Batching	20%-33% (percent below baseline)	
3.1.2. Laser-Induced Breakdown	54,000 GJ (for a single-furnace glass	$220 - $440 million per year (U.S.)

Paper Section/Technology Name	Energy Savings Estimate	Cost Savings Estimate
Spectroscopy for Improved Control of Glass Feedstock	factory producing 250 tons per day)	
3.2. Batch and Cullet Preheating		
3.2.1. Raining Bed Batch and Cullet Preheating	527 MJ per ton of glass produced	
3.2.2. E-Batch Preheating Technology	15%-25% (percent below baseline)	
3.3. Emerging Technologies for Glass Melting		
3.3.1. Oscillating Combustion	2-27% (percent below baseline)	
3.3.2. Segmented Melter		
3.3.3. Plasma Melter	50%-70% (percent below baseline)	
3.3.4. Submerged Combustion Melting	5%-20% (percent below baseline)	55%-80% (percent below baseline, capital cost)
3.3.5. In-flight Melter		
3.3.6. Porous Burners		
3.3.7. Glas Flox® Flameless Burner		
3.3.8. Microwave Heating		
3.4. Process Control Technologies		
3.4.1. Glass Furnace Model: Glass Melting Simulation Software	5% (percent below baseline)	
3.4.2. Image-Based Control of Glass Melting Furnaces	2%-8% (percent below baseline)	
3.5. Conditioning and Forming		
3.5.1. Oxy-fuel Fired Forehearths	64% (percent below baseline)	
3.5.2. Single Stage Forming		15% (percent below baseline)

This paper focused on technologies that are promising but have not yet been commercialized. Therefore, further research is needed to improve and optimize these technologies in order to make them available for commercial use. In addition, the description of these technologies often used information from only a handful of sources regarding energy saving potential, cost, and other characteristics. Conducting independent studies and validation on the fundamentals, development, and operation of these emerging technologies can improve the quality of publicly available information for a wide range of stakeholders.

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