doi: 10.21307/ACEE-2021-035

INFLUENCE OF GLASS FURNACE AGE, CULLET SHARE AND GLASS COLOR ON THE GLASS PRODUCTION ENERGY EFFICIENCY

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Received: 20.09.2021; Revised: 15.11.2021; Accepted: 15.11.2021

Abstract
Glass manufacturing is a high-volume process during which large quantities of natural raw materials are turned into commercial products, with large amounts of non-renewable resources and energy consumed in the process. Therefore, it is critical to support the transition to higher levels of energy and material efficiency, CO_2 emissions and increased resource productivity.
The main objective of this paper is to present the results of a simulated correlation study considering the age of the glass furnace, cullet share in the process and batch composition of the glass produced, and their influence on the coefficient of energy consumption. In this work, the quoted dependencies were observed. Identification of relations influencing energy consumption enables optimization of particular technological parameters of the process.
Industrial companies are expected to reduce energy consumption in several ways, including technological improvements in production processes and recover lost energy, and recycling of recyclables from waste. Therefore, studies such as this one allow industrial companies to research and learn from, and implement solutions to meet global regulatory and market expectations.

Keywords: **Energy consumption; Energy efficiency; Energy coefficient; Cullet share; Glass Color; Glass production; Simulation.**

1. INTRODUCTION

Glass-making operations in EU27 are often interlinked to location-specific economic conditions and energy polices, as well as fluctuations of fuel and electricity prices, availability of resources and supplier network in the value chain. About 80–90% of the process heat in European glassmaking industries are produced by means of natural gas which is the main cause of the carbon dioxide (CO_2) emissions of the industry. The ambitious EU27 objectives associated with the significant reduction of CO_2 emissions and importance of energy efficiency is gradually increasing the pressure on the European glass industry for achieving deep decarbonisation by 2050 [1].

Glassworks have the potential to improve energy consumption factor while maintaining productivity. Improving energy efficiency at a glass plant should be approached from several directions. First, a glass plant uses energy for equipment such as motors, pumps and compressors. These important components require regular maintenance, good operation, and replacement, when necessary.

A second and equally important area is the proper and efficient operation of the processes. Process optimization and ensuring that the most productive technologies are in place are key to realizing energy savings in a plant's operation [2].

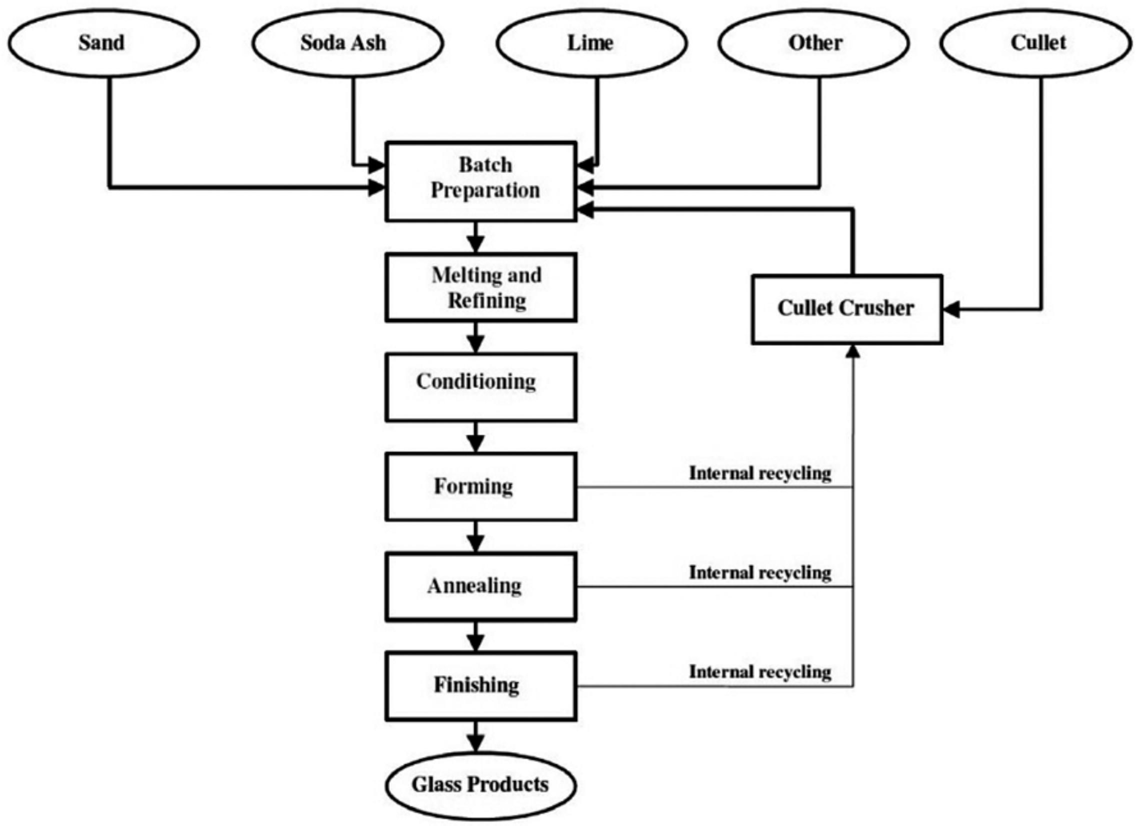

Figure 1.
The process of manufacturing quality container glass [3]

Figure 1 shows in the form of a block diagram, the process of manufacturing high quality container glass. During batch preparation, raw materials are selected and mixed. The main ingredients are high-quality silica (sand), limestone and soda ash, and (for container glass) feldspar with many other substances that can be added. The composition of the glass batch can greatly influence the outcome of the final product, in terms of its chemical, electrical, mechanical and thermal properties. Therefore, proper proportioning and mixing of these materials is critical to the product characteristics. The various soda-lime glass products are basically similar, but differ in the proportions of the ingredients and in the additives specific to each application. In addition to minerals, cullet is also used with the ratio up to 90% of the weight of the batch for container glass.

Next the batch is melted in a furnace at very high temperature (between 1430°C and 1600°C) to remove impurities and transform the raw materials from the batch. As these crystalline materials become molten, chemical reactions associated with melting, dissolution, volatilization and oxidation-reduction occur that turn it into glass. The use of cullet in the batch allows for energy savings as glass melting requires less heat and natural gas. The limiting factor is primarily the availability of suitable (selected) cullet containing no impurities.

Melting can be done in many different types and sizes of furnaces incorporating different fuels and energy intensities. This depends on the desired end product. About 80% of the glass produced in the world is melted in regenerative furnaces [3]. These furnaces include electric boosting that increase output, reduce fuel consumption and emissions at the manufacturing plant.

Refining is the stage where the molten glass is freed of bubbles, homogenized and heat conditioned. This chemical and physical process occurs in the melting chamber. The desired quality and properties of the glass determines how much refining is done. The average residence time of molten glass in the furnace is 24 to 72 hours. Melting of raw materials consumes about 60–70 percent of the total energy used to make glass.

The final product takes shape during forming. As it moves from the melting tank to the forming machine, the molten hot glass with proper viscosity. The forming must take place quickly, since the glass become rigid as it cools. Depending on the final product, the glass container forming process can vary widely.

The main novelty of this work is the analysis of data from practices in the glass container industry. It presents the results of the energy consumption analysis of glass mass production considering the age of the glass furnace, the proportion of cullet in the process and the batch composition.

2. METHODOLOGY

The specific consumption of energy of glass melting furnaces depends mainly on the following factors [4]:

– batch composition – which results in a glass color,
– the amount of cullet,
– moisture content of batch and cullet,
– compactness of the batch – e.g., powdered or pelletized batch,
– insulation and sealing of the furnace and the heat exchangers,
– temperature level within the furnace depending on the desired glass quality, furnace design,
– air factor of the combustion process,
– burners settings,
– continuous or discontinuous melting process,
– efficiency of the combustion air preheating in recuperator or regenerator,
– melting load of the furnace.

In the glass industry there are many opportunities to reduce energy consumption in a cost effective manner. Many energy efficiency improvement practices and energy-efficient technologies have been identified that can be implemented at the component, process, systems, and organizational levels.

The present work consisted in creating a simulation of energy consumption reflecting the assumptions of Best Available Technologies in the glass industry. The analysis was based on collected data from the last few years of the glass melting process in the glass industry, consistent with the practice in the glass industry. Energy consumption was investigated as a function of cullet proportion, molten glass color and furnace agening.

2.1. Impact of furnace age on the coefficient of energy consumption

Continuous process of drawing molten glass though the furnace erodes the internal lining which results in increased heat losses. The regenerative heat recovery system is particularly prone to ageing. The regenerators essentially comprise two large structures which are sited on either side of the furnace and contain a honeycomb of brickwork. The regenerators operate in a cyclic process of 20 to 30 minutes duration. At any time one of regenerators is being heated by the hot furnace gases (1500°C) as they leave the combustion chamber whilst the other regenerator is returning heat to the combustion air (input temperature 60°C). Every 20–30 minutes their roles reverse. The regenerator brickwork is thus constantly being cycled between very hot and relatively cold gas inputs. Unsurprisingly, the heat recovery system deteriorates with time.

Once commissioned modern container furnaces should run continuously for about 12 years before it undergoes a hot repair that should extend its life by further 3–4 years. The arduous duty that these furnaces perform results in a slow but inexorable deterioration in the integrity of the refractory materials. The result is a reduction in furnace efficiency as the furnace ages. The thermal efficiency of a furnace may deteriorate by 25% over a typical 12 years campaign. The aging effect has not been widely studied and, whilst most furnace operators agree that the effect is not a linear trend, in the absence of detailed data a simple linear relationship is adequate for most purposes [5].

Globally, with the growth of the glass industry, considerable efforts have been placed on the optimization of the melting tank, where the most energy-consuming steps of glass making take place. Improvements can be made at the end of the campaign life of an existing furnace, or when constructing a new furnace [6].

2.2. Impact of cullet share in batch composition on the energy efficiency

Glass cullet is a high-value raw material since its usage results in [7]:

– reduction of consumption of raw materials (silica sand, soda, dolomite, etc.),
– reduction of CO_2 emission that is generated while melting the raw materials,
– prolongation of the service-life of the glass fur-

nace, because of the lower melting temperature of glass cullet than of the raw materials,
- reduction in the consumption of energy sources (usually: natural gas, petroleum) for melting the raw materials, which means also emissions of NO_x, SO_2 and particulates into the environment,
- almost 100% recyclable, out of 100 kg of glass cullet 100 kg of glass containers can be produced.

2.3. Impact of the color of the produced glass on the energy efficiency

There are a number of additives used to color and impart unique properties to glass. Common colorants include iron, chromium, cerium, cobalt and nickel. Amber glass is created by adding ferrous sulfide or iron pyrites. Cobalt and nickel oxides are used to decolorize the yellow-green tint that results when the melt is contaminated with iron. When mixed with iron and cobalt, selenium creates glass with an amber color. Each chemical reacts at different temperature levels and requires a different proportion of energy.

This paper presents the simulation results of the energy consumption of glass mass production considering the age of the glass furnace, cullet share in the process and the color of the glass produced. For the purpose of the simulation, based on the reports of technologists in the industry for more than 10 years, a database was created where all the information about the glass melting process and different production conditions such as glass pull, cullet share, glass color, energy consumption, etc. was collected.

The data were analyzed using Python programming language along with NumPy, Pandas, MatPlotLib and Seaborn libraries [8].

The simulation results are presented with the use of heatmaps (Figure 3 and 4) comparing the energy consumption ratio as a multiplier of the indicative values relating to one ton of melted glass resulting from the best available techniques (BAT) conclusion which after adding up the electrical energy with the thermal energy of the fuel is [9]:

$$\text{Total energy per one ton of melted glass} = 2\,560\,000\ \text{BTU} \quad (1)$$

3. RESULTS

Technological knowledge is very important in a manufacturing company, in any industry. The currently developed systems supporting the design of technological processes allow for the sharing of various methods of data presentation, their transformation and exchange.

Scientific know-how is a set of information about a technological process carried out in strictly defined realities of a given enterprise. It is a dynamic set, i.e., it changes over time as the parameters of the technological process change. It is assumed that experience in industry can be properly processed at the stages of building the advisory system.

In the case described, the effect of furnace age and cullet contribution on energy consumption expressed in BTUs of energy consumed per ton of glass melted is analyzed. Table 1 shows a summary of the number of records for each glass color in the database for the simulated glass furnace analyzed, the indicated value represents the number of days of melting a given glass color, mostly flint color as the most popular one. The days when the glass mass was discolored in the furnace were not included in the study. This collation allowed a clear investigation of the effect of cullet share and furnace age on the energy efficiency of glass melting in this flint color.

The assumed cullet contribution to the melting of each glass color over the years presents a range from zero to one hundred percent. However, as practice in the glass industry indicates, it does not yet exceed the 80% level. The color variations allow to study the differences in energy consumption for glass melting purposes. Therefore, the changes in the composition of the glass set for the first 5 years and the penultimate year were investigated, each with a 10% sample share in the simulation database for each color.

Table 1.
Dataframe with melting of particular glass colors over several years for the analyzed furnace

Glass color	Number of records	Data share, %
Flint	3200	80
Green	400	10
Amber	400	10

The best way to graphically present the data is by using a heatmap, where the individual values contained in the matrix are represented by a color scale, visualizing the data through color differences. The chart shows where the highest values are. The solution used in the heatmaps is the presentation of data changes over time (periods, years). The results show the energy consumption multiplier by cullet over a period of time (years).

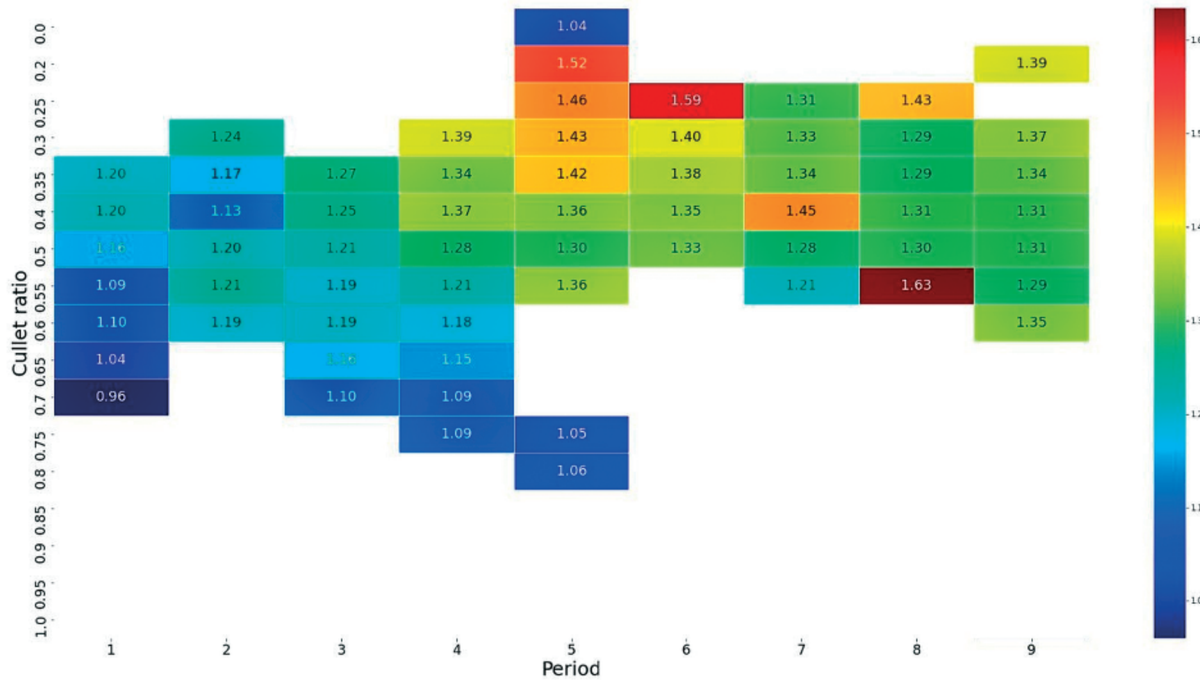

Figure 2.
Energy consumption multiplier factor for all melted colors

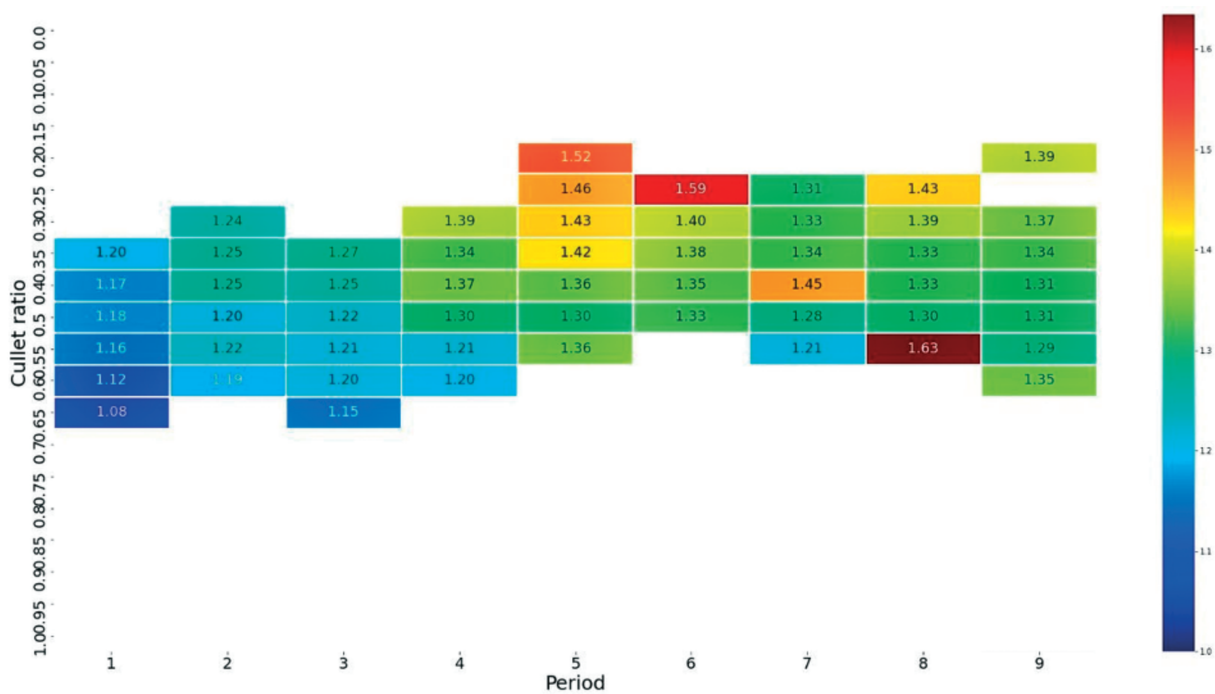

Figure 3.
Energy consumption multiplier factor for flint color

Figure 2 presents heatmap process energy consumption multiplier factor to match them with the BAT conclusions for all colors melted over the years, while Figure 3 is only for the flint color. The factors on heatmaps represent the ratio of energy consumed in the production of a tonne of glass, it is a multiplier of total energy per one ton of melted glass (Equation 1). Process energy consumption in the case studied in this paper is defined as the amount of energy consumed (the sum of electrical energy and thermal energy) for the purpose of melting one ton of glass according to the BAT conclusions.

For melting of colored glass, the heatmap provides with information about higher multiplier, for the described years and colors tiles with lower values are presented, the melting of a ton of colored glass has a lower energy demand. The white fields indicate that the condition consistent with the axes did not occur in the case studied.

4. DISCUSSION

From many factors influencing the energy demand of the glass melting process described in the methodology section, the analyses in this paper focus on the impact of aging of glass furnaces, cullet share, batch composition and glass color as having a direct impact.

In this study, the characterization of the glass set in terms of its moisture content and compactness was omitted because such data were not collected in the industrial data. It would be worthwhile to look into these relationships in further studies.

The insulation and sealing of the furnace and heat exchangers, the temperature level inside the furnace, and the efficiency of preheating the combustion air were not included in the analysis because of their indirect effects on energy consumption for glass mass production. The lining condition of the furnace and heat exchangers, its heat losses depend on the age of the furnace. The temperature level in the glass furnace determines the consumption of thermal fuels.

The furnace design, air factor of the combustion process, burner settings have been omitted because it is impossible to capture them from the broad area of the glass industry. It would be necessary to lean on a specific case, a selected glass furnace.

Analysis of data collected from several years of the glass industry using Python programming and its libraries, mainly Seaborn, allowed to effectively investigate the simulated model on the factors known from the literature affecting the energy efficiency of glass mass melting.

The paper presents a comparison of the energy demand of melting just one color of glass, flint, in terms of different cullet shares and as the furnace ages. Heat maps allow direct conclusions to be drawn from the analysis of the collected data. At a higher cullet ratio, the process of melting one ton of glass requires less energy, which increases energy efficiency. At the same level of cullet utilization in the melting process, when the furnace ages, the energy requirement increases. The results of the analysis conducted in this paper confirm that theoretical knowledge coincides with reality in the glass industry.

5. CONCLUSION

Glass manufacturing facilities are energy intensive and represent a significant opportunity for energy savings. Emerging technologies for glass manufacturing as well as available plantwide approaches can be applied to glass operations and supporting systems to facilitate energy savings and greater overall efficiencies.

The anticipated savings associated with some of the individual factors outlined above may be relatively small, but the cumulative effect of these measures across the facility could potentially be quite large. For all of the energy efficiency measures outlined above, individual glass plants should conduct further research into the economics of these measures, as well as the applicability of various individual measures to their own unique manufacturing practices, to assess the feasibility of their implementation [2].

The application of the best practices in implementing support systems can significantly reduce overall consumption, provide environmental benefits, and economic benefits to the plant. The increased efficiency will reduce costs and strengthen the glass industry.

In this study, data collected from the glass industry over several years created a simulation and confirmed the effect of cullet contribution and furnace age on the energy efficiency of the glass melting process. For the same cullet proportion as the age of the furnace increases, more energy is required to melt the same number of tons of glass, while the cullet proportion significantly affects the energy requirement of the melt. The study showed that the production of glass from cullet requires less fossil fuel (natural gas) consumption than the production of the same glass from virgin raw materials.

Comparing the heat maps for all melted colors and for flint only, it can be seen that the melting efficiency of colored glass is higher due to its composition.

It is a good practice in the glass industry to track the energy demand of glass production by an increasingly older furnace, so that furnace rebuilding can be justified in terms of operating costs [10].

REFERENCES

[1] Schmitz, A., Kamiński, J., Scalet, B.M., Soria, A. (2001). Energy consumption and CO_2 emissions of the European glass industry. *Energy Policy*, 39, 142–155.

[2] Worrell, E., Galitsky, C., Masanet, E.R., Graus W. (2008). Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry: An ENERGY STAR® Guide for Energy and Plant Managers, Energy Star.

[3] Zier, M., Stenzel, P., Kotzur, L., Stolten, D. (2021). A review of decarbonization options for the glass industry; Energy Conversion and Management: X Volume 10, June 2021, 100083.

[4] Handbook for Glass Technologists (2006). Derived from NCNG course, TNO International Course on Glass Technology, 2006.6. Kovaćec M., Pilipović A., Štefanić N., Impact of Glass Cullet on the Consumption of Energy and Environment in the Production of Glass Packaging Material, Recent Researches in Chemistry, Biology, Environment and Culture, ISBN: 978-1-61804-060-2.

[5] Hartly, A. (2014). Study of the Balance between Furnace Operating Parameters and Recycled Glass in Glass Melting Furnaces, Glass Technology Services, September 2014.

[6] Pellegrino, J.L. (2002). Energy and Environmental Profile of the US Glass Industry, Energetics Incorporated Columbia Maryland, April 2002.

[7] Vellini, M., Savioli, M. (2008). Energy and environmental analysis of glass container production and recycling, *Energy 34*(2009) 2137–2143, Roma.

[8] www. https://docs.python.org/3/license.html

[9] Scalet, B.M., Garcia Munoz, M., Sissa, A.Q., Roudier, S., Delgado, Sancho L. (2013). Best Available Techniques (BAT) Reference Document for the Manufacture of Glass, Industrial Emissions Directive 2010/75/EU, 2013.

[10] Testa, M., Malandrino, O., Sessa, M. R., Supino, S., Sica, D. (2017). Long-Term Sustainability from the Perspective of Cullet Recycling in the Container Glass Industry: Evidence from Italy, Sustainability 9, 1752.