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Energy and Material Flow Evaluation with CO_2 Emissions in the Glass Production Process

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Abstract

Glass manufacturing is an energy-intensive process with high demands on product quality. The wide usage of glass products results in a high end-product diversity. In the past, many models have been developed to optimize specific process steps, such as glass melting or glass forming. This approach presents a tool for the modeling of the entire glass manufacturing process for container glass, flat glass, and glass fibers. The tool considers detailed bottom-up energy and material balance in each step of the processing route with the corresponding costs and CO_2 emissions. Subsequently, it provides the possibility to quantify optimization scenarios in the entire glass manufacturing process in terms of energy, material and cost flow efficiency.

Keywords

Energy Efficiency, Glass Industry, Energy Balance, Container Glass, Flat Glass, Glass Fiber

1. Introduction

The industrial sector has been identified by the European Union (EU) as one of the main drivers of energy consumption and emissions. Since the agreed target was to reduce net emissions by at least 55% by 2030 compared to 1990 and to be the first climate neutral continent by 2050 [1], the national laws of the various EU member states regarding industrial activities are continuously updated to meet the EU directives. The energy-intensive industry sectors, such as the glass industry, are especially affected by this kind of legislation. Therefore, the need for maximizing efficiency and minimizing emissions is getting more focus. Apart from the environmental consequences, the economics are also changing radically in terms of CO_2 pricing models and customer awareness [2]. Digitalization of industrial processes is a key to reasonable and cost-effective tools for generating data, which can form the basis for action in the planning of new production plants and the optimization of existing ones.

As material compositions of glass industry products vary broadly depending on type, chemical, mechanical and optical properties it is necessary to integrate detailed calculation procedures including material composition to model the actual processes. CO_2 emissions by the glass industry are not only affected by the intensive energy input, but also by the decomposition of carbonates within the raw input materials, which occurs in the glass-melting furnace. To reduce CO_2 emissions and energy input overall, the cullet fraction in the batch plays an important role. The thermodynamics and chemistry of this kind of melting process is well documented and broadly researched already [3] [4].

Software solutions for modeling operations in continuous glass furnaces [5] [6] [7] [8] and energy benchmarking of continuous glass furnaces [9] [10] [11] have been developed to support design and operation, as these types of furnaces are operated and maintained for many years after construction. The forming processes are also already simulated by various models in order to be able to improve them [12] [13] [14] [15]. In order to quantify all relevant material and energy flows, inclusive estimation of CO_2 emissions, over the entire manufacturing process of glass products, a more general method is proposed in this paper.

The so-called Energy Efficiency Evaluator (E^3-Tool) is an Excel-based tool for modelling the manufacturing process of glass containers, flat glass and glass fibers. It was developed on the basis of a tool for the modeling of the foundry product routes [16]. From energy consumption data, process time and mass flow input, energy and mass balance are computed for each process step on the way from the batch to the packaged product. The three representable branches for the production of container glass, flat glass and glass fiber cover about 95% of the glass products produced in the EU, as shown in **Table 1**.

Clarity on the specific and total energy consumption, material flow and emissions by the detailed observation of the thermodynamic processes in each specific manufacturing process step was seen as a key feature. A bottom-up approach

Table 1. Glass production in the European Union by branch [17].

Glass products	2010		2015		2020	
	in 1000 t	share	in 1000 t	share	in 1000 t	share
Flat glass	10,099	31%	9641	29%	10,773	30%
Container glass	19,990	61%	20,319	62%	22,331	62%
Glass fiber	1016	3%	1080	3%	1132	3%
Tableware & Crystal	713	2%	677	2%	853	2%
Other glasses	1004	3%	1218	4%	762	2%
TOTAL	32,822	100%	32,935	100%	35,851	100%

enables the comparison of different scenarios with variable energy source types brought into a process in terms of their cost efficiency and emissions. For this purpose, the E^3-Tool offers, for example, the possibility to consider oxy-fuel solutions, blending hydrogen with natural gas, as well as the dynamic modular scenario evaluation of the alternative processing solutions/units and its impact on the overall process.

The results are given in form of pivot tables and include the electrical energy consumption, the consumption of fuels, the total energy consumption, waste gas losses and surface losses of the specific process step in relation to one ton of glass product or per product itself. Furthermore, the amount of emitted CO_2 and the energy costs are calculated per process step. Thus, the E^3-Tool can be used for the calculation of energy-saving potentials, as support for internal audits up to the calculation of energy and material costs for product launches.

The innovative aspect of the tool is the possibility for the complete mapping of the energy, material, cost flow and CO_2 emissions in the entire process chain for three main branches in the glass industry. Application of the principle of dynamic linkage in the programming and calculation concept allows the consideration of all occurring process-specific circumstances in the production chain. Furthermore, the changes in the energy supply, such as alternative fuels, in a unit and their effects on the entire process can be evaluated. The model offers the possibility for the variation of different technical solutions for the specific processing step and subsequently an effective amortization time determination.

2. Glass Production Process

In the production of glass products, the respective glass experiences very similar process steps, regardless of whether container glass, flat glass, glass fiber or glass wool are produced. In the first step, raw materials and cullet are mixed to form a batch, which in the next step is melted into glass in a suitable furnace. In the forming process, the four products mentioned are formed from molten glass. The deviations in these four process routes are widest in this step. The post-treatment is again very similar and includes annealing and quality control. Therefore, the production process was divided into four main processes:

- Batch preparation
- Glass melting
- Forming
- Post-treatment (post-forming)

Each of these main processes contains main units that allow a detailed representation of the production process. The production of glass products includes many units that are not directly involved in the manufacturing process, but are nevertheless very important (e.g.: cooling units, supply of compressed air). Such units are called sub units and differ from the main units in a way that no direct product flow occurs. For each main unit, all possible sub units are provided and can be dynamically selected. **Figure 1** shows the structure of main processes,

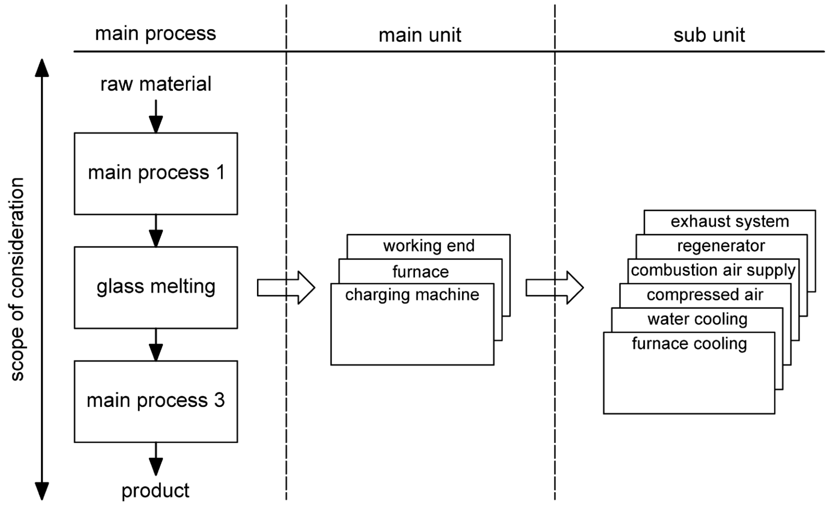


Figure 1. Structure of the main process, main unit and sub unit using the main process of glass melting as an example (based on [18]).

main units and sub units using the example of the main process glass melting. By defining the main processes, the respective main and sub units are enabled.

All these units are considered as black boxes in which mass and energy flows are balanced. The production process of glass products is quite extensive. In the following, this is briefly outlined and shown how it can be represented with the four main processes and the associated units. For a more detailed description, please refer to respective cited literature.

2.1. Batch Preparation

The high diversity in the glass industry leads to a wide range of raw materials used. These can be divided into five categories: glass formers (network formers), fluxes, stabilizers, colorants and fining agents. The most important glass former is silica sand. However, since silica sand has a very high melting temperature, fluxes are used to make the glass melting process more energy efficient. These are usually in carbonate form and will be described in more detail in **Section 3.1** [19] [20] [21].

Batch preparation includes silos, conveyors, elevators, weighers and mixers used to mix raw materials and cullet into batch. Since little energy is consumed compared to the rest of the production process [2], these are combined into one main unit batch preparation. **Figure 2** shows the main units and sub units of the main process batch preparation and the associated material and energy flows. The main process of batch preparation includes another main unit, batch preheating. Here, the batch is preheated via exhaust gas.

2.2. Glass Melting

This main process represents the heart of the production process, in which the most energy is consumed. The carbonates contained in the raw materials are decomposed under CO_2 release and the batch is melted to glass in four steps

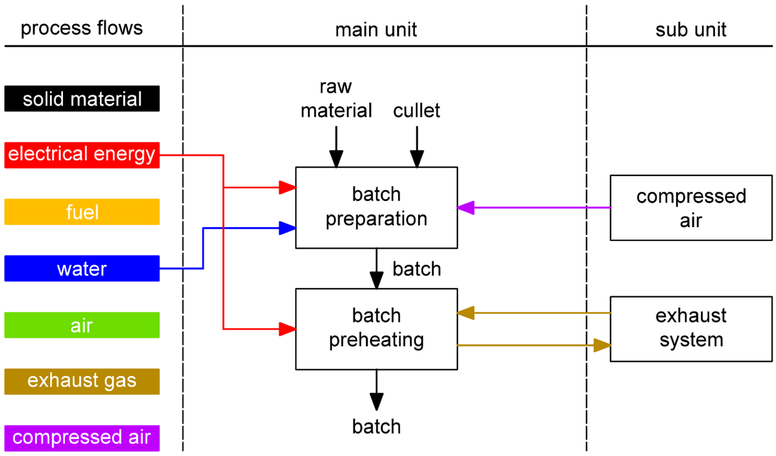


Figure 2. Process flows, main units and sub units of the main process batch preparation.

(melting, sand grain dissolution, fining and conditioning). The molten glass must be heated to temperatures of around 1600˚C to ensure sufficient fining and homogenization. More than 98% of the world's glass production is carried out in continuous glass furnaces [6]. The energy supply to the furnaces is provided by natural gas or electric power. In regenerative cross-fired or end-fired glass furnaces, energy is extracted from the hot exhaust gas via regenerators and returned to the combustion air. In most cases, these furnaces also feature electric boosting, in which electrodes immersed in the melt provide additional energy input. In addition to regenerative furnaces, recuperative furnaces, oxy-fuel furnaces and purely electrically powered furnaces are also used [19] [22] [23].

All these furnaces can be modeled with the main unit furnace shown in **Figure 3**. The sub unit combustion air supply can be used to select between air, oxygen-enriched air or pure oxygen as oxidant. In exhaust system, process data for exhaust gas cleaning and heat extraction from the exhaust gas can be taken into account. The sub units combustion air supply, regenerator and exhaust system are provided for each natural gas consumption occurring in the process. The sub units shown can be selected or deselected as required.

The main process glass melting provides three sub units for cooling purposes. Furnace cooling cools the furnace walls with an air flow to increase lifetime. Water cooling is used to cool electrode holders or the charging machine. Pyrometers or other measuring equipment are often cooled with compressed air.

The working end fulfills the function of distributing the molten glass to the individual production lines and conditioning the melt. If no forehearths are used in the forming process (e.g. float glass), the molten glass must be cooled down to the required processing temperature in the working end. To achieve a homogeneous temperature distribution, the working end is heated with natural gas or electrically [24].

2.3. Forming

In this step, a distinction is made between container glass, flat glass and glass

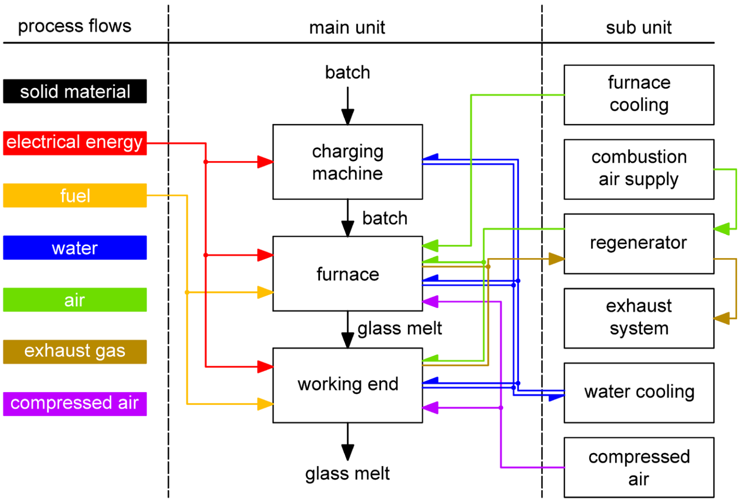


Figure 3. Process flows, main units and sub units of the main process glass melting.

fiber. In the production process of container glass, shown in **Figure 4**, the glass is transported to the forming machine via forehearths. The forehearth, like the working end, has the function of conditioning the molten glass. In the container glass industry, containers have been manufactured mainly in so-called individual section machines (IS-machines) [19] [20]. In this process, so-called gobs are formed from the molten glass at the forehearth end, which drop into the molds of the IS-machines. In these molds, glass containers are formed from the gobs in a two-stage press-blow process or blow-blow process. In both processes, a parison is formed in the blank mold, whereby in the press-blow process this is done by a metal plunger and in the blow-blow process by compressed air. The parison is then transferred to the finishing mold, where it is blown into the finished container using compressed air. The gobs cool down from approx. 1300˚C to 400˚C - 600˚C. The released heat is dissipated via cooling air [15] [19] [25].

If maintenance or mold changes are carried out on a IS-machine, the continuously formed gobs are ejected, cooled and transported back to the batch preparation as process cullet. In order to protect the finished containers from damage, they are sprayed with a layer of tin oxide by the main unit hot end coating. The containers are transported further on conveyor belts with the main unit transport. Depending on the requirements, the containers can be heated by gas burners or cooled by air. The molds of the IS-machines have to be lubricated at a regular interval, which means that the surface of the containers produced directly afterwards does not meet the quality standards. These bottles are ejected in the main unit transport and returned to the process as process cullet [19] [25] [26].

According to [19], 95% of flat glass produced in the EU is produced by the float glass process. In this process, the molten glass is poured onto a molten tin bath and forms a continuous ribbon. An equilibrium between gravitational force and interfacial tension results in a continuous thickness of the glass ribbon, which can be influenced by water-cooled top rollers. In this process, the molten

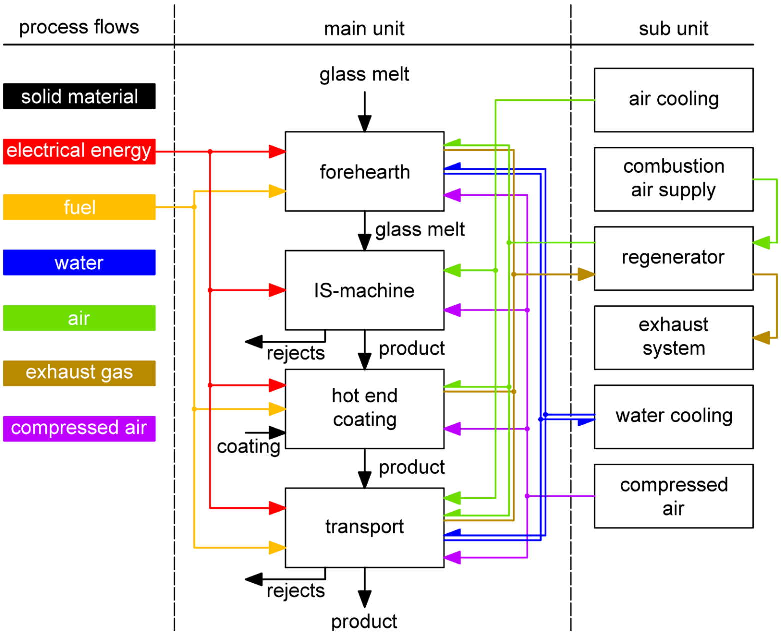


Figure 4. Process flows, main units and sub units of container glass production in the main process forming.

glass cools from approx. 1100˚C to approx. 600˚C of the product. In order to produce flat glass with a suitable surface finish, oxidation of the molten tin must be prevented. This is ensured by a slightly reducing atmosphere, which is obtained by purging with a gas mixture of nitrogen and hydrogen [19] [25].

As shown in **Figure 5**, the production of flat glass in the E^3-Tool differs from the production of container glass only by the main unit float bath. The remaining main units are quite similar to those used for container glass production, with minor changes such as sulfur dioxide instead of tin oxide for hot end coating. Corresponding main units and associated sub units can be selected as required to represent the flat glass production process.

In the production of glass fibers, a basic distinction is made between continuous and discontinuous glass fibers. There are also differences in the way the molten glass is supplied. This can be done directly from raw materials or indirectly via previously produced marbles which are remelted [27].

Continuous glass fibers are produced by the continuous fiber-drawing process. In this process, the molten glass is divided into individual filaments at the end of the forehearth via many small nozzles in platinum plates (bushing), cooled drastically via water nozzles, high air flows, or water-cooled metal plates and then drawn off via a rotating mechanism. The filament diameter can be influenced by the speed of the drawing [19] [25] [27].

Discontinuous fibers can be produced by several processes. In centrifugal fiber drawing, for example, the molten glass is poured into a hollow drum whose outer wall is perforated with many small holes. Centrifugal force acts through a rotating motion and numerous filaments are formed. Near the drum, downward blowers or burners are installed to elongate the produced fibers. If thinner fibers

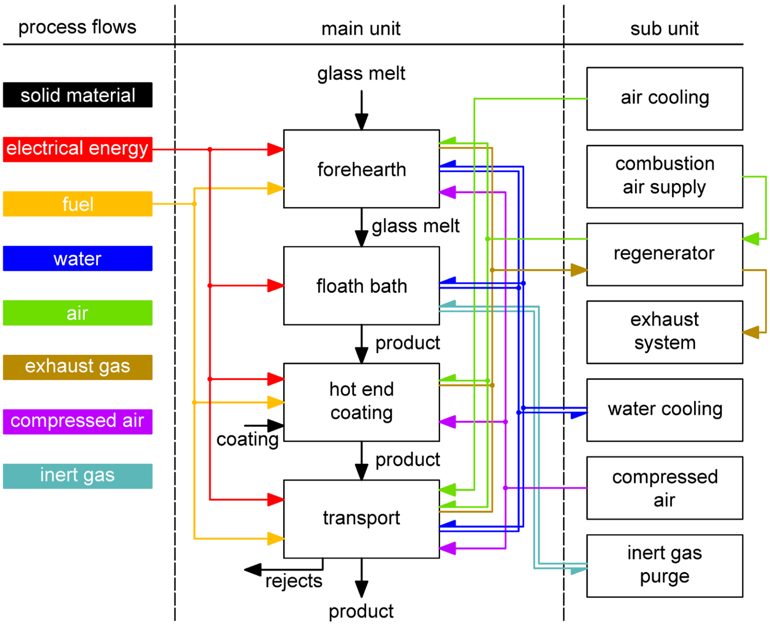


Figure 5. Process flows, main units and sub units of flat glass production in the main process forming.

are produced, this can be done with the flame attenuation process. Similar to the production of continuous glass fibers, the fibers are drawn through bushings and then formed into discontinuous glass fibers by a horizontally mounted burner [19] [25].

Depending on the purpose for which the glass fibers are produced (e.g. reinforcement of plastics, heat-insulating glass wool), various coatings are applied to the fibers. Film formers, coupling agents, pH modifiers and lubricants are typical coating components [19] [27].

The processes for glass fiber production can be represented by the main unit fiberization process shown in **Figure 6**. The remaining main units correspond to those of glass container and flat glass production process.

2.4. Post-Treatment

All glass products produced require subsequent treatment after forming. To reduce stresses, container glass and flat glass are cooled in an annealing lehr under controlled conditions. To prevent surface damage, the products are given a cold end coating. Flat glass and glass fiber are cut to size, with rejects returned to the process as process cullet. Containers are partially decorated. Finally, the products are inspected for quality and packaged. All these process steps can be represented and modeled in the main process post-treatment in **Figure 7**.

3. Methodology of Calculation

The following describes the balancing of energy and mass flows. Particular attention will be paid to the energy required in the furnace to produce glass melt from batch.

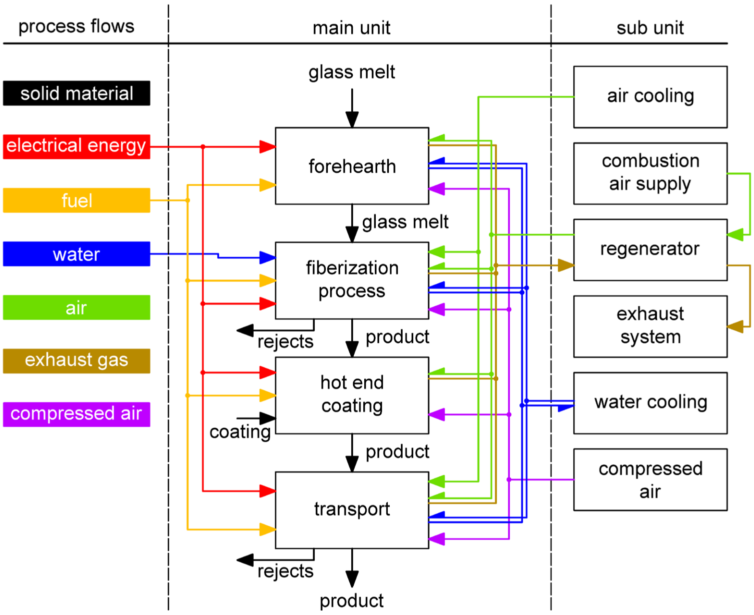


Figure 6. Process flows, main units and sub units of glass fiber production in the main process forming.

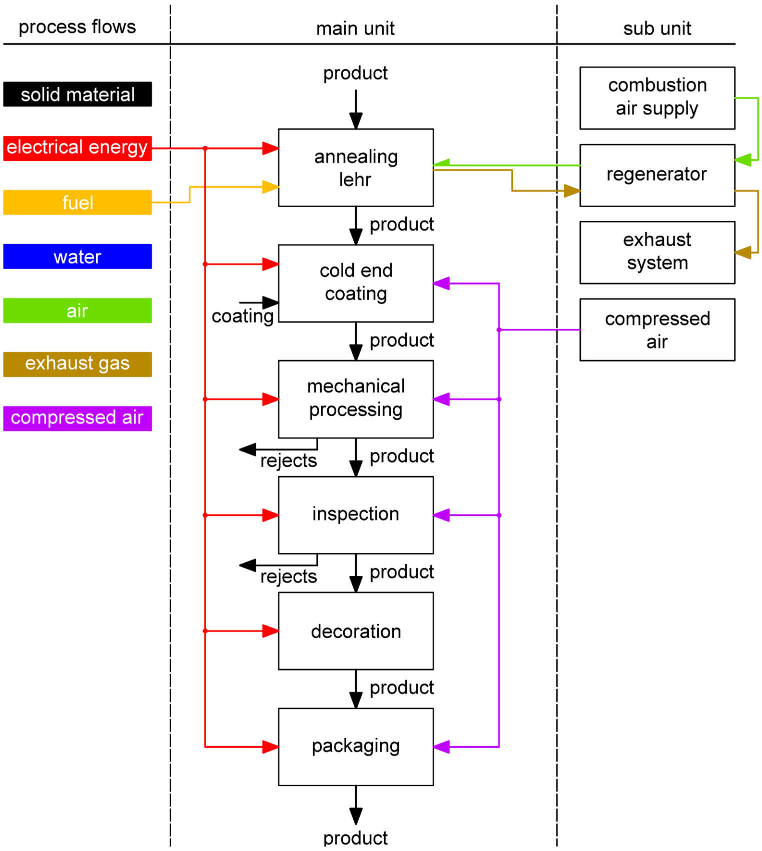


Figure 7. Process flows, main units and sub units of the main process post-treatment.

3.1. Batch-to-Melt Conversion

Since glass is used in so many different ways, there are also many different glass compositions. **Table 2** shows the most important oxides for various industrial glass compositions. These oxides, except silica sand, are mostly introduced via carbonate raw materials, such as soda ash for Na_2O or limestone for CaO [28]. The decomposition of the carbonates releases large amounts of CO_2, which must be removed from the glass melt to obtain glass of suitable quality. However, other gases can also be formed, such as H_2O vapor from batch moisture [29]. As the temperature rises, the solubility of the gases in the melt decreases and the melt becomes permeated with fine gas bubbles [30]. Therefore, fining agents are added to the batch, which decompose only at high temperatures and release large amounts of gases that form large bubbles, which in turn absorb existing small gas bubbles and bring them to the surface. The most commonly used fining agent today is sodium sulfate [31]. Sodium sulfate reacts with silica sand above 1200˚C and thermally decomposes above 1400˚C with massive release of SO_2 an O_2:

$$Na_2SO_4 + n\text{SiO}_2 \rightarrow Na_2O \cdot n\text{SiO}_2 + SO_2 + \frac{1}{2}O_2 \tag{1}$$

Any SO_3 formed is converted to SO_2 and O_2 as in an atmosphere of sulfur and oxygen at temperatures between 1000˚C and 1600˚C there is mainly SO_2 with small amounts of SO_3 or S_2 [32].

The different compositions of glasses lead to different thermodynamic properties, such as the energy required for melting or heat capacity. Although glasses and glass melts have a homogeneous state, thermodynamic properties can be determined with good accuracy via a so-called crystalline reference system (CRS) [33]. Using the CIPW norm, the mass percentages of the oxides occurring in the melt can be used to determine the compounds formed in the glass melt and, subsequently, the glass. For this purpose, 26 rules have been defined, which were actually defined for petrology, but can also be applied to glasses [34]. For typical industrial glasses, it has been shown that they can be characterized by a predominant quartet, typically consisting of more than 85% of the oxides on a molar basis [33]. Conradt [35] has described a method for calculating the eight most

Table 2. Examples of typical industrial glass compositions [23].

Glass	Oxide contend [wt%]							
	SiO_2	B_2O_3	Al_2O_3	Na_2O	K_2O	CaO	MgO	Others
Container glass								
Flint	72.5	-	1.5	14.0	0.5	11.0	-	<0.05 Fe_2O_3; 0.2 SO_3;
Green	72.0	-	1.0	15.0	-	8.5	2.0	0.4 Fe_2O_3; 0.05 SO_3; 0.25 Cr_2O_3
Float glass	70.0	-	1.0	14.0	0.8	9.0	5.0	0.08 Fe_2O_3; 0.3 SO_3
E-glass	54.5	6.6	14.0	0.8	0.2	22.1	0.6	0.5 TiO_2; 0.2 Fe_2O_3; 0.5 F_2
Glass wool	64.0	4.5	3.5	15.5	1.2	7.0	3.0	0.25 Fe_2O_3; 0.15 SO_3

frequently formed compounds by the mass fractions of the oxides for typical industrial glasses. These are used to calculate the energy required for batch-to-melt conversion.

3.2. Exploited Heat in Glass Furnaces

Since it is generally difficult to measure the losses via the furnace wall, these are calculated via the heat balance. Figure 8 shows the heat balance of a continuously working glass furnace. The heat input (in), the heat contained in the exhaust gas (off), the heat recovered (re), and the heat exhausted through the stack (stack) can be calculated using combustion calculations described in **Section 3.3**. When the exploited heat in the molten glass (ex) is also known, the wall losses (wo, wu) of the furnace can be determined from the energy balance [36].

The exploited heat H_{ex} specifies the heat required to produce a glass melt from the batch. It is composed of two parts, the so-called chemical heat demand ΔH°_{chem} and the physically stored heat $\Delta H_{melt}(T)$ at the temperature at which the glass melt is extracted from the furnace (relative to 25˚C) [36].

$$H_{ex} = (1-\mu_c)\Delta H^{\circ}_{chem} + \Delta H_{melt}(T), \tag{2}$$

The chemical heat demand corresponds to the enthalpy difference of batch on one side and glass and batch gases on the other side at 25˚C and 1 atm [36]:

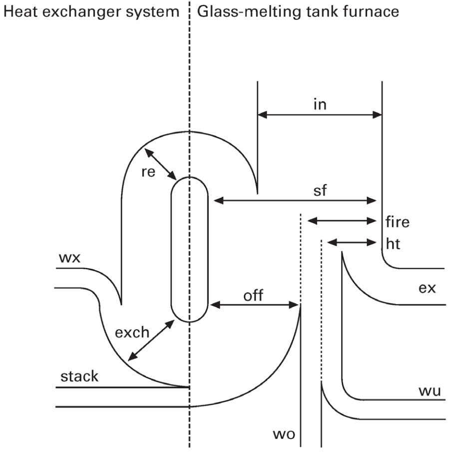
$$\text{batch}(25^{\circ}\text{C}) \rightarrow \text{glass}(25^{\circ}\text{C}) + \text{batch gases}(25^{\circ}\text{C}), \tag{3}$$

which is written as

$$\Delta H^{\circ}_{chem} = H^{\circ}_{glass} + H^{\circ}_{gas} - H^{\circ}_{batch}. \tag{4}$$

Since cullet does not contribute to ΔH°_{chem} this is taken into account via the mass fraction of cullet μ_c in Equation (2). The standard heats of the batch H°_{batch} and the individual batch gases H°_{gas} used in Equation (4) are calculated using the weighted sum of the standard heats of the respective raw materials and gases.

The heat $\Delta H_{melt}(T)$ physically stored in the glass melt is calculated as



in: heat input by fuel and electricity;
sf: heat set free in the furnace;
fire: heat transferred to the furnace body;
ht: heat transferred to the basin;
ex: exploited heat;
off: heat stored in the off-gas leaving the heat exchanger;
stack: heat stored in the off-gas leaving the heat exchanger;
exch: heat transferred to the body of the heat exchanger;
re: heat recovered by the air passing through the heat exchanger;
wu: wall losses through the basin;
wo: wall losses through the lining of the combustion space;
wx: wall losses of the heat exchanger.

Figure 8. Heat balance of a continuous working glass-melting tank [35].

$$\Delta H_{melt}(T) = H_{melt}(T) - H^{\circ}_{glass}. \tag{5}$$

H°_{glass} is the standard heat of rigid glass and $H_{melt}(T)$ is the heat of a glass melt at the temperature T. Both can be calculated by the following set of equations [34]:

$$H^{\circ}_{glass} = \sum_k n_k \left(H^{\circ}_k + H_{vit,k}\right), \tag{6}$$

$$H_{1673,melt} = \sum_k n_k H_{1673,melt,k}, \tag{7}$$

$$c_{p,melt} = \sum_k n_k c_{p,melt,k}, \tag{8}$$

$$H_{melt}(T) = H_{1673,melt} + c_{p,melt}(T - 1673), \tag{9}$$

where k stands for the compound in the corresponding CRS and n_k for the corresponding mole fractions. In Equation (6) H°_k is the standard enthalpy of the crystalline solid at 25˚C, $H_{vit,k}$ is the vitrification enthalpy. In Equation (7) $H_{1673,melt,k}$ stands for the heat of the melt compound at 1400˚C (1673 K) and $H_{1673,melt}$ is total melt enthalpy at 1400˚C (1673 K). $c_{p,melt,k}$ in Equation (8) is the heat capacity of the glass compound, $c_{p,melt}$ is the heat capacity of the glass melt. Most industrial glasses consists of multicomponent mixtures, whose thermodynamic quantities for the calculation of Equation (6) to Equation (9) can be taken from **Table 3** [35].

3.3. Heat Input via Combustion

For the quantification of the total combustion heat input and heat contained in the exhaust gas, following procedure has been implemented.

Volumetric flow of the combustion gases is calculated using specific quantity of the exhaust gas from the stoichiometric equation for the hydrocarbon combustion, including pure hydrogen, with air and/or oxygen:

$$\begin{aligned} &C_mH_n + \left(m + \frac{n}{4}\right)\lambda O_2 + \left(m + \frac{n}{4}\right)\frac{1-\xi_O}{\xi_O} N_2 \\ &\rightarrow mCO_2 + \frac{n}{2}H_2O + \left(m + \frac{n}{4}\right)(\lambda - 1)O_2 + \left(m + \frac{n}{4}\right)\frac{1-\xi_O}{\xi_O} N_2 \end{aligned} \tag{10}$$

Table 3. Thermodynamic data of compunds k employed to represent the CRSs of industrial glasses [35].

compound k	$-H^{\circ}$	H_{vit}	$-H_{1673,melt}$	$c_{p,melt}$
	[kJ/mol]	[kJ/mol]	[kJ/mol]	[kJ/mol·K]
Fe_2O_3	823.4	45.2	550.2	142.3
$FeO{\cdot}SiO_2$	1196.2	36.7	962.3	139.7
$K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	7914	106.3	6924.9	765.7
$Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	7841.2	125	6870.1	648.1
$MgO{\cdot}SiO_2$	1548.5	46.6	1318	146.4
$Na_2O{\cdot}2SiO_2$	2473.6	29.3	2102.5	261.1
$Na_2O{\cdot}3CaO{\cdot}6SiO_2$	8363.8	77.3	7372.6	786.6
SiO_2	908.3	6.9	809.6	86.2

with λ as air-fuel equivalence ratio, defined as ratio of the actual to stoichiometric condition and ξ_O as volume fraction of oxygen in the oxidant. Obviously, for the pure oxygen combustion, the last term on the right- and the left-hand side in the equation above equals zero. For the given fuel mixture composition, Equation (10) is used considering volumetric fractions of the fuel with corresponding oxidant. For the known composition of the exhaust gas (products), volumetric concentration n_i of each species in the exhaust gas can be easily obtained:

$$n_i = \frac{\upsilon_i}{\sum_j \upsilon_j}, \tag{11}$$

where υ_i stand for stochiometric coefficients of each species on the product side. Additionally, the gases produced during the batch-to-melt conversion in the furnace are also taken into account. Thus, for the given exhaust gas temperature T_{off} and the temperature dependent specific heat capacity of the combustion products $c_{p,i}(T)$, the heat contained in the exhaust gas H_{off} is calculated using following expression:

$$H_{off} = \dot{m}_{fg} \cdot \sum_i \mu_i c_{p,i}(T) \cdot T_{off}. \tag{12}$$

Exhaust gas mass flow $\dot{m}_{fg}$ is obtained from the ideal gas equation, μ_i represents mass fraction of each component.

Total heat of combustion for the fuel mixture H_{comb} with f_i as a fuel fraction, where H_{fi} denotes enthalpy of combustion of each fuel component is computed as follows:

$$H_{comb} = \sum_i f_i H_{fi}. \tag{13}$$

Additionally, the total energy input from the combustion process includes inflow enthalpy H°_{inlet} from oxidant and fuel on inlet:

$$H^{\circ}_{inlet} = \dot{m}_f \cdot \sum_i f_i c_{p,i}(T) \cdot T_{in} + \dot{m}_{ox} \cdot \sum_i f_{iox} c_{p,i}(T) \cdot T_{in}, \tag{14}$$

$\dot{m}_f$ and $\dot{m}_{ox}$ stand for total fuel and oxidant mass flow on inlet, f_i and f_{iox} are corresponding fractions of each mixture component and T_{in} is inlet temperature.

3.4. Energy and Mass Balance

Energy balance (conservation) in the system is defined by the first law of thermodynamics:

$$\delta W_t + \delta Q_e + \sum_i dm_i (h_i + e_{ei}) = dU + dE_e, \tag{15}$$

where δW_t denotes work done by system, δQ_e heat exchange, h_i is transported enthalpy with the mass dm_i. Similarly, e_{ei} stands for the transport of the external energy; dU and dE_e quantify internal and external energy change in the system, respectively.

The special form for the non-adiabatic (open) stationary system, with periodical processes being approximated as stationary as well, considering work done by system be equal to zero, energy balance within each constitutive unit in the process is computed by following relation:

$$Q_{tot\_e} + H_{tot\_in} - H_{tot\_out} + P_{tot} = 0. \tag{16}$$

In the equation above P_{tot} is electrical energy and index *tot* stands for the total cumulative value for the energy flows within the unit in the process, Q_{tot_e} denotes heat exchange, $H_{tot\_in} - H_{tot\_out}$ enthalpy transport in the system.

As the energy is transported by the mass *m* in the entire process, mass conservation is solved for each material mass flow:

$$\sum_i m_{in} - \sum_i m_{out} = dm, \tag{17}$$

with m_{in}, m_{out} as the mass flow at the inlet and outlet boundaries and dm as the total mass change in the system.

Tracking distinctively the total mass flux for primary materials, rejects and cullet material as the process parameter throughout each computational step, the mass needed at the first input for the planed product per unit is recursively computed using following expression:

$$m_{i-1} = \frac{m_i}{1 - \left(\frac{m_{r,i}}{m_{p,i} + m_{c,i}}\right)}, \tag{18}$$

m_i is the mass of the product in the *i*-th process step, and $m_{c,i}, m_{p,i}, m_{r,i}$ are cullet, primary materials and rejects, respectively. First iteration step *i* is done at the last production step with end-product mass, subsequently decreasing to the first process step. Previous result is used to recalculate any energy and material costs or consumption in the process to equivalence per unit at any processing step.

The total flux Φ_{tot} of any physical quantity Φ in the production process and/or any main or sub unit can be computed by following equation:

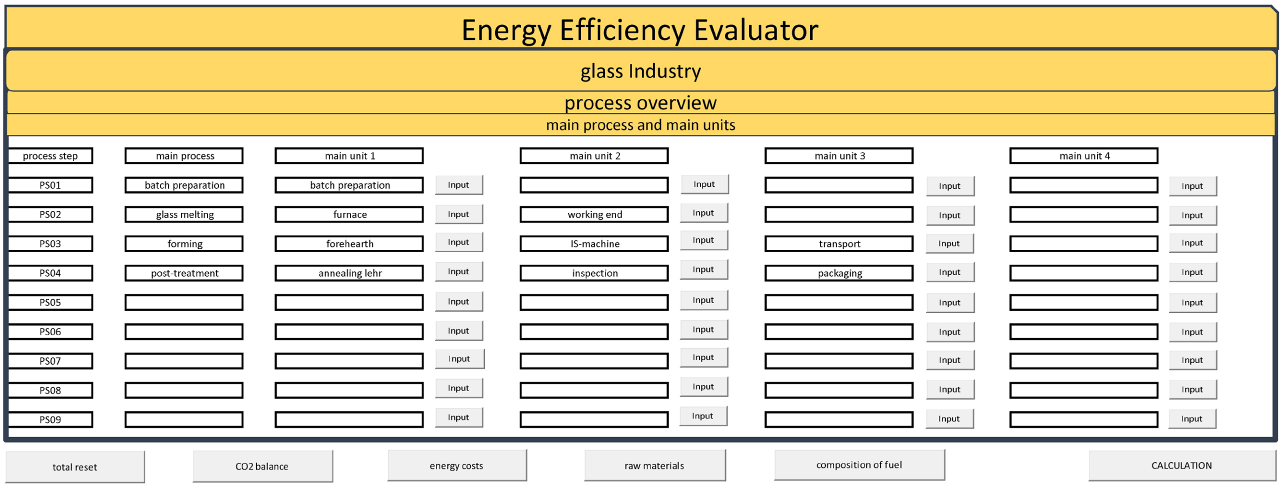
$$\Phi_{tot} = \sum_i \sum_j \left(\Phi_{i,j} + \sum_k \Phi_{i,j,k}\right), \tag{19}$$

with *i* defined as the main process index, *j* as the number of main units in the main process and *k* as a the number of sub units in the main unit of the process. From the relation above, sub calculations can be used to quantify costs/consumption, flux of the physical property in any predefined module or the module intensity relative to the overall system.

4. Realization of the Energy Efficiency Evaluator

4.1. Process Representation and Data Input

The E^3-Tool user interface is used to display the glass manufacturing process. The desired main processes can be selected via drop-down menus. For a more detailed representation of the manufacturing process, up to four main units per selected main process can be defined via drop-down menus, as shown in **Figure 9**.



Energy Efficiency Evaluator

glass Industry

process overview

main process and main units

process step	main process	main unit 1	main unit 2	main unit 3	main unit 4
PS01	batch preparation	batch preparation			
PS02	glass melting	furnace	working end		
PS03	forming	forehearth	IS-machine	transport	
PS04	post-treatment	annealing lehr	inspection	packaging	
PS05					
PS06					
PS07					
PS08					
PS09					

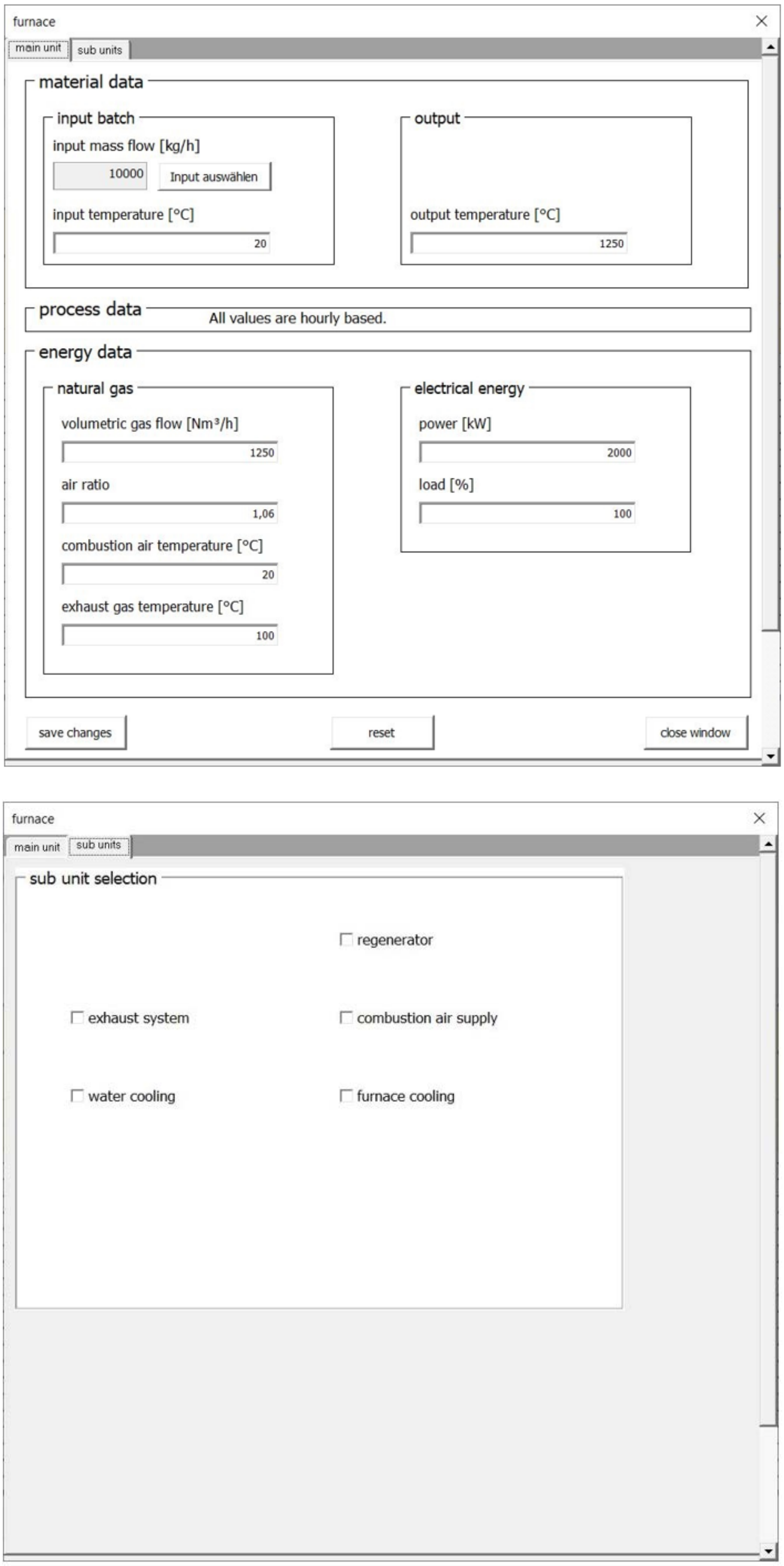
Figure 9. User interface of the E^3-Tool with a selection of main processes and main units for the representation of a container glass production.

The "Input" button next to each main unit in the process step calls up an input form, in which process parameters can be defined. **Figure 10** shows an exemplary input form for the main unit furnace in the main process glass melting, with the input parameters for material, process and energy data. Material data concerns temperatures and mass flows of raw materials, batch, glass melt or glass product. In the furnace shown in **Figure 10**, 10,000 kg/h batch at 20˚C is melted to glass and extracted at a temperature of 1250˚C. The intermediate heating of the glass melt up to 1600˚C for sufficient fining and subsequently cooling down to the extraction temperature ultimately results in heat loss. The output mass flow is calculated on the basis of the batch composition and the resulting amount of CO_2. For units of the main processes forming and post-treatment, the mass flow and the temperature of the rejects is defined in this section.

A batch process can be represented via process data. Most process steps in industrial glass production are continuous and the section process data does not require any data input, *i.e.* the computation is referenced to an hour. Batch processes only occur in units of the main processes batch preparation or post-treatment, such as decoration. In case of the furnace in **Figure 10**, no input fields for the process data section are provided, since it is a continuously operating furnace.

The energy data section for this particular unit includes the energy introduced by electrical energy or fuels and associated parameters, as air ratio, combustion air temperature and exhaust gas temperature. The composition of the oxidant, possible combustion air preheating via regenerators and exhaust gas treatment are represented via sub units as the part of the superordinate main unit. Input data for sub units are entered into separate forms, which can be selected on the additional tab of each main unit, as shown in **Figure 10**.

Figure 11 shows the input form for the sub unit combustion air supply in which, in addition to the electrical energy input, the oxidant used can also be



input mass flow [kg/h] 10000

input temperature [°C] 20

output temperature [°C] 1250

All values are hourly based.

volumetric gas flow [Nm³/h] 1250

air ratio 1,06

combustion air temperature [°C] 20

exhaust gas temperature [°C] 100

power [kW] 2000

load [%] 100

☐ regenerator

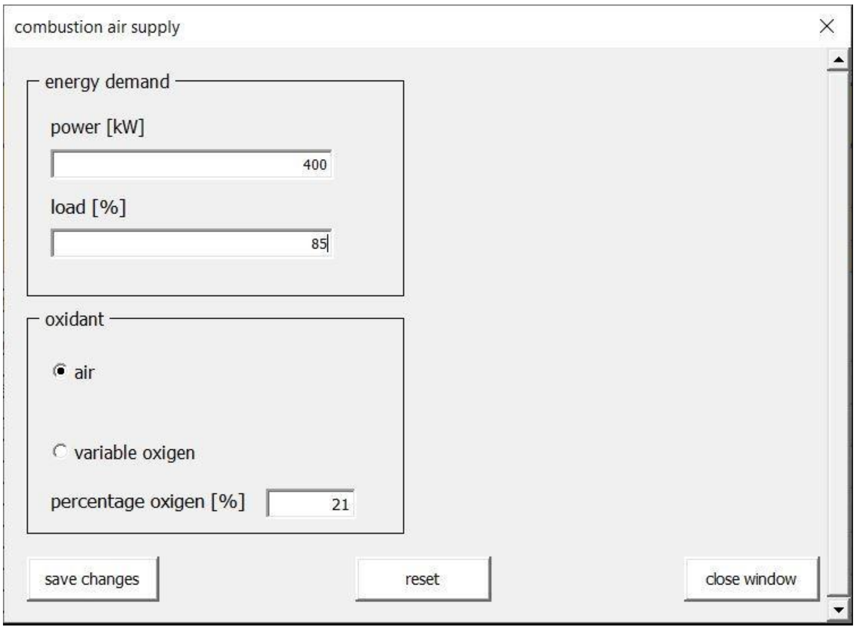
☐ exhaust system

☐ combustion air supply

☐ water cooling

☐ furnace cooling

Figure 10. Input form for the main unit furnace with the input parameters for material, process and energy data (top) and second tab with the selectable sub units (botton).



combustion air supply

energy demand

power [kW] 400

load [%] 85

oxidant

● air

○ variable oxigen

percentage oxigen [%] 21

Figure 11. Input form for the selected sub unit combustion air supply.

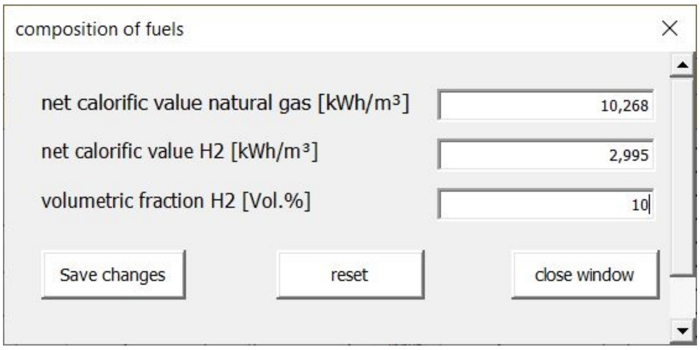
defined. By selecting the oxygen content of the oxidant, oxygen enrichment up to pure oxy-fuel combustion can be modeled.

For the calculation, not only process-specific data but also general data are required. These can be defined via the buttons “CO_2 Balance”, “energy costs”, “raw materials” and “composition of fuel” at the bottom of **Figure 9**. “CO_2 Balance” takes into account upstream emissions of natural gas and CO_2 emitted by the energy source mix used. The costs for the respective fuel or electrical energy are defined via “energy costs”. CO_2 emissions during melting of the raw materials, as well as the composition of the melt, are strongly dependent on the batch composition, which is defined via general input option “raw materials”. In “composition of fuel” the net calorific value of natural gas and alternatively hydrogen enrichment of natural gas can be defined, as shown in **Figure 12**.

4.2. Presentation of Results

The results of the calculation are presented in the form of pivot tables and bar charts based on them. The following results are given per ton of glass product or per product itself:

- Specific energy consumption broken down by
    - Specific electrical energy consumption
    - Specific consumption of fuels
    - Specific total energy consumption
    - Specific surface losses
    - Specific exhaust gas losses
- Specific CO_2 and SO_2 emissions
- Material flow during the manufacturing process
- Specific energy costs



composition of fuels

net calorific value natural gas [kWh/m^3] 10,268

net calorific value H2 [kWh/m^3] 2,995

volumetric fraction H2 [Vol.%] 10

Figure 12. Input form for the composition of fuel.

For the presentation of a diagram of specific energy consumption in this paper, a virtual container glass manufacturing process with a tonnage of 150 tons of glass containers per day was designed. The consumption data used is based on an actual industrial process but has been heavily modified for data protection reasons. **Figure 13** shows the specific energy consumption per ton of glass product for the main units (MU) and the respective sub units (SU) for the main processes of this virtual plant. The high energy consumption for melting the glass can be seen, but also the effectiveness of the regenerator, which recirculates the difference in total energy consumption and exhaust gas loss to the furnace by preheating the combustion air. The energy of the exhaust gas entering the regenerator is represented as total energy consumption, and the energy of the exhaust gas leaving the regenerator as exhaust gas loss. The heat dissipated by the sub unit cooling air from the glass containers produced during the main process forming is also evident. Due to the falling temperature of the glass containers, the surface losses are greater than the energy supplied from the main unit IS-machine onwards to the main unit packaging.

Figure 14 shows cumulative energy consumption for the main and sub units in each main process for a specific 200 g end product. This approach enables a bottom-up energy and material balance per product and in the last consequence direct product based cost accounting analysis.

Figure 15 shows the specific energy costs for each process step in the manufacturing of container glass product. For the evaluation, an electricity price of 200 €/MWh and a natural gas price of 100 €/MWh were assumed.

Using the electrical energy consumption, the natural gas consumption and the CO_2 released during the melting of the carbonate-containing raw materials into glass, the CO_2 emissions are calculated for each process step, as shown in **Figure 16**.

The specific SO_2 emissions and the material flow during the manufacturing process are also given in the form of bar charts and pivot tables. With regard to the calculated SO_2 emissions, it should be noted that these are calculated via the sulfur-containing refining agents introduced into the furnace. It is assumed that all the sulfur introduced leaves the glass melt in the form of SO_2. Since this means that the sulfur remaining in the melt and additional sulfur introduced by

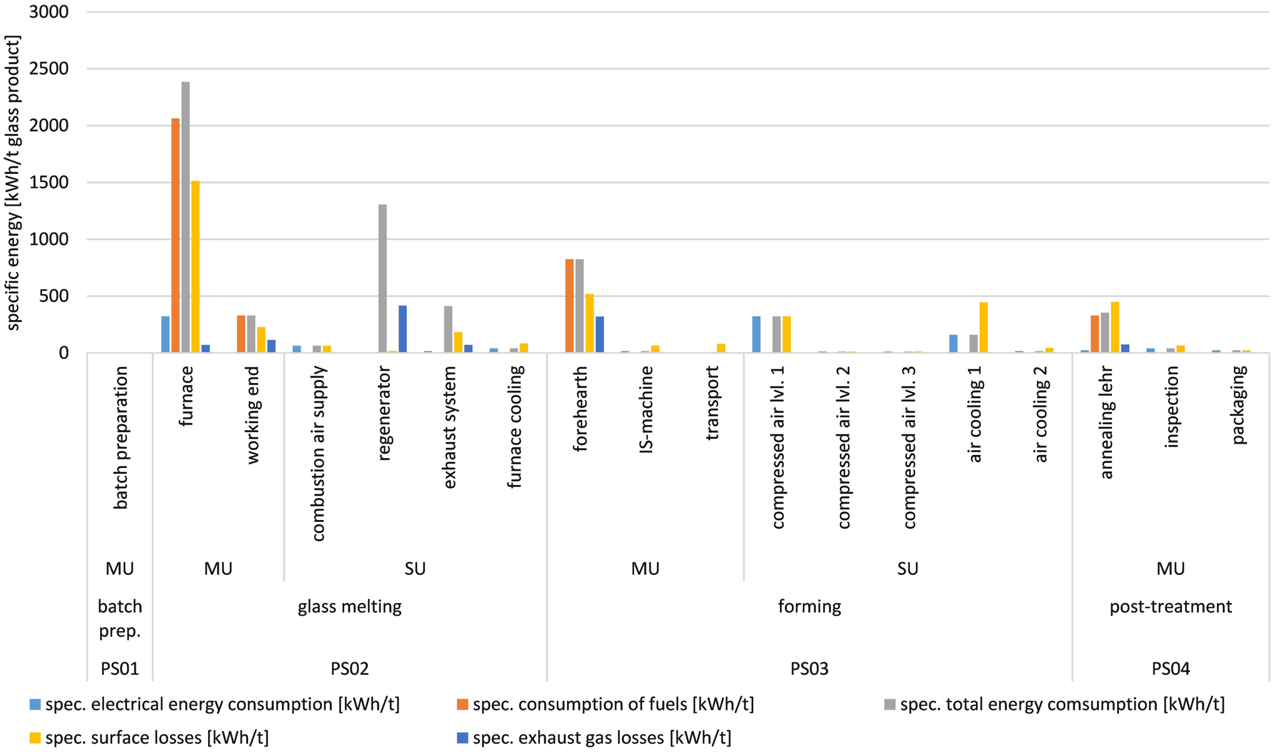


Figure 13. Specific energy consumptions of the individual process steps of a virtual glass container manufacturing process.

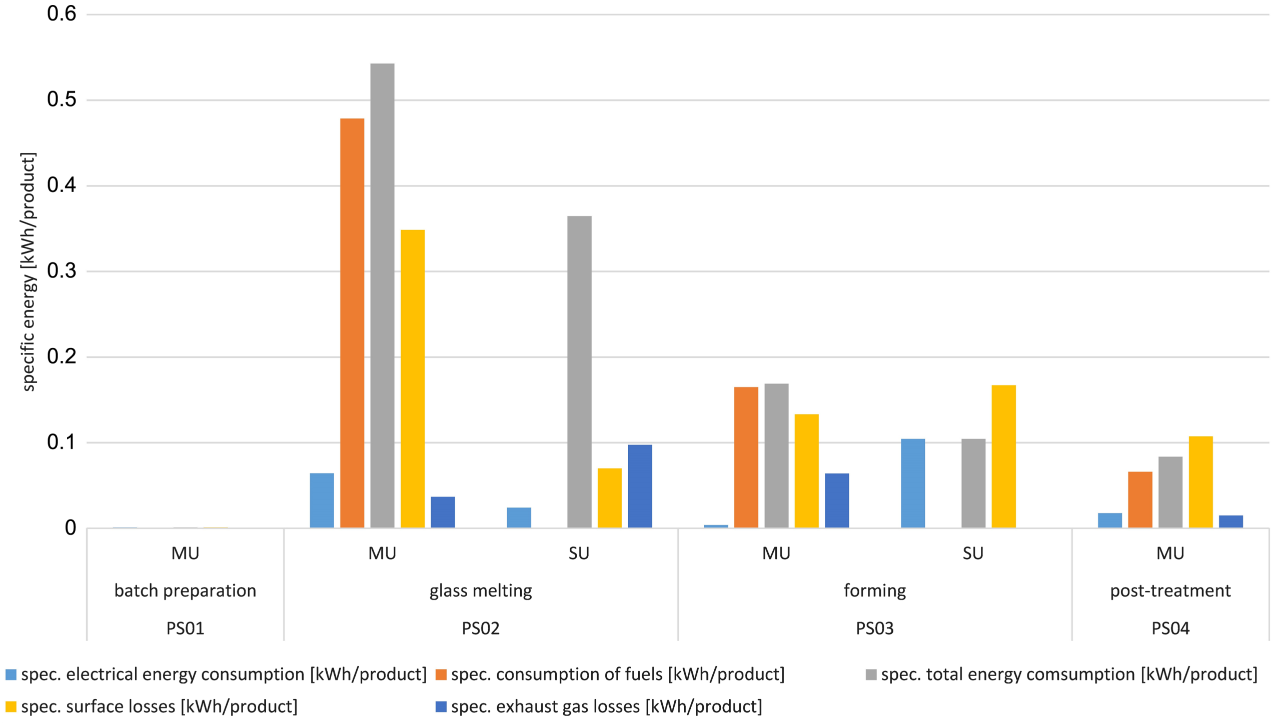


Figure 14. Specific energy consumptions of the main processes of a virtual glass container manufacturing process.

impurities in the raw materials are not taken into account, these results are to be understood as approximate values.

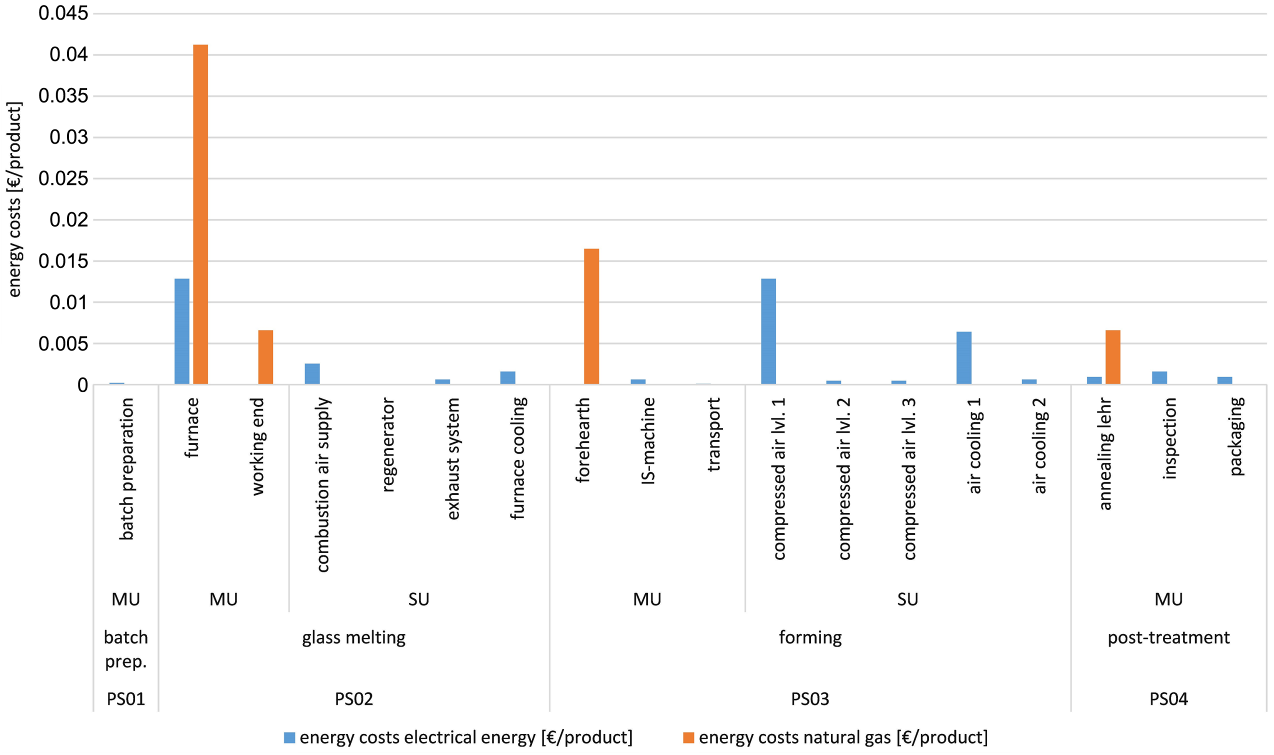


Figure 15. Specific energy costs of the individual process steps of a virtual glass container manufacturing process.

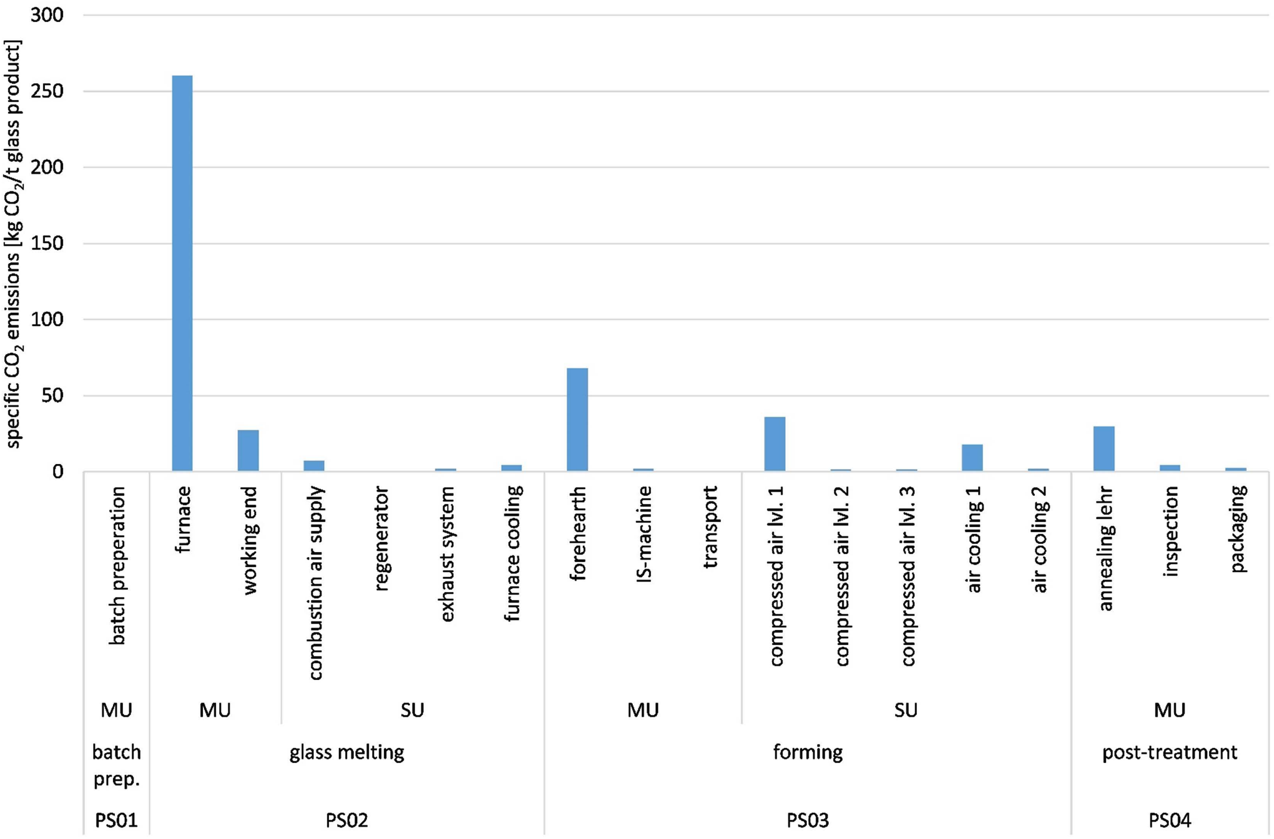


Figure 16. Specific CO_2 emissions of the individual process steps of a virtual glass container manufacturing process.

5. Conclusions

With the E^3-Tool, the entire manufacturing process of glass products can be evaluated in terms of energy and material flow. With a bottom-up approach and the consideration of thermodynamic laws, an energy balance is computed taking into account the detailed energy content of the respective material flows. The output data on specific electrical energy consumption, consumption of fuel, total energy consumption, surface and waste gas losses per process step allow a deeper understanding of the process and enable the evaluation of possible savings potentials. In addition to the energy data, statements are also made regarding CO_2 and SO_2 emissions.

The production of a glass melt from carbonate raw materials releases CO_2 and thus the feed quantity of raw materials does not correspond to the quantity of glass melt produced. During the further processing of the melt into products, additional losses occur. Through the recursive mass flow calculation, the tool supports the determination of the necessary amount of raw material for the production of certain glass products. Thus, with the detailed bottom-up energy and material balance in each processing step with the consideration of the corresponding costs, the tool provides a well-founded cost analysis for the manufactured products.

At present, data input is still done manually using specially created data input forms. With an extension of the tool with an automatic data query from a process control system, energy-saving measures can be continuously monitored.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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