

Soda–Lime–Silica Glass Batch Optimization: A Composition-Constrained Framework for Cullet Use

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Abstract

Optimizing glass batches requires balancing the benefits of recycled glass against constraints on composition, melting behavior, and product quality. This study formulates a framework for evaluating cullet use in soda–lime–silica glass production. The approach combines oxide mass balances, carbonate-related carbon dioxide accounting, energy and cost boundaries, and composition-dependent viscosity constraints. Five illustrative scenarios with nominal cullet contents of 0–80% are examined using descriptive calculations and dominance analysis. In the supplied scenarios, increasing cullet content from 0 to 60% corresponds to reductions of 27.3% in energy consumption, 23.2% in carbon dioxide emissions, and 10.0% in cost. The additional improvement between 60 and 80% is smaller, but the 80% scenario still has the lowest values for all listed objectives. Consequently, these inputs do not establish an intermediate optimum or a Pareto trade-off. Analytical mass balances show that composition-matched cullet can reduce carbonate-derived emissions while increasing the dependence of final glass chemistry on the composition of the recycled feed. The numerical values are illustrative inputs rather than experimentally validated outcomes or predictions generated by an implemented optimizer. The framework provides a basis for batch screening and identifies the measurements needed to determine a defensible operating range for a specific product and furnace.

Keywords: Recycled glass; oxide mass balance; carbonate decomposition; melt viscosity; multiobjective optimization; energy efficiency; feedstock variability.

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1. Introduction

Glass batch formulation connects raw material selection with furnace operation and the properties of the finished product. An economical recipe must supply the required oxides, convert to a homogeneous melt within the available residence time, and remain compatible with the intended forming process. Environmental performance adds another requirement: material substitutions should reduce energy demand and carbon emissions without increasing product rejection. The European

Commission's reference document for glass manufacturing treats efficient energy use, raw material consumption, and recycling as related aspects of process improvement [1].

In soda–lime–silica glass, the relationship between batch composition and melt behavior requires careful attention. Silica provides the principal glass-forming component, while the other oxides influence processing and service properties. Adjusting the oxide composition can change viscosity, crystallization behavior, thermal expansion,

and chemical durability. These relationships make it inappropriate to select a formulation solely because it has a lower raw material price or a lower nominal processing temperature [2,3].

Cullet offers a complementary route because it supplies glass-forming oxides in material that has already undergone batch conversion. Its use can replace part of the virgin mineral feed and reduce the quantity of carbonate-bearing ingredients entering the furnace. Nevertheless, the final glass composition must remain within product specifications. A recent survey by Deng et al. examined commercial container and float glasses and evaluated opportunities for composition adjustment using property models and theoretical energy calculations [4]. Their analysis illustrates why glass chemistry and energy requirements should be evaluated together.

The physical form of recycled material also matters. Deng et al. investigated container glass batches containing 15 wt% briquettes made from cullet fines and reported changes in decomposition and silicate reaction kinetics [5]. This finding supports the inclusion of feed preparation in batch assessment, but it does not establish a universal benefit for every cullet size distribution or source. Ueda et al. showed that silica dissolution, gas evolution, and foaming depend on batch thermal history [6]. Ferkl et al. subsequently coupled heat transfer and conversion kinetics in a container-glass melting model [7]. These studies indicate that composition alone cannot describe batch-to-glass conversion.

Two further issues affect formulation decisions. First, viscosity predictions require a model appropriate to the composition and temperature range. Fluegel's statistical viscosity model demonstrates the importance of composition information and the limitations of prediction outside the underlying data domain [8]. Second, recycled feed must be characterized as a material stream with variable chemistry and cleanliness. The Joint Research Centre's technical assessment of glass cullet provides a basis for considering these quality requirements [9].

The practical problem addressed here is how to connect these considerations in a transparent formulation framework. A cullet percentage by itself does not specify a complete batch, and favorable energy or cost values do not demonstrate that a formulation satisfies quality

constraints. The aim of this study is therefore to formulate an oxide-constrained approach to cullet selection and examine what can be concluded from a small set of supplied numerical scenarios. The contribution is a consistent connection between raw batch mass, retained oxide yield, emissions accounting, and feasible formulation selection.

2. Methods

2.1. Study design and analytical scope

This work combines a theoretical formulation framework with a descriptive analysis of five illustrative scenarios. It is not presented as an experimental furnace study. The numerical dataset contains nominal cullet contents, temperature indicators, energy consumption, carbon dioxide emissions, and costs. Complete recipes, material assays, furnace records, repeated measurements, and the derivation of the scenario values are unavailable. The values are therefore treated as supplied inputs for comparison.

The material system comprises silica, sodium carbonate, calcium carbonate, a magnesium carbonate equivalent, and composition-characterized cullet. These components represent a simplified soda–lime–silica batch. They do not constitute a complete industrial recipe. A plant-specific model may also require alumina-bearing materials, dolomite, fining agents, colorants, and corrections for moisture or volatilization.

The reference basis for the proposed mass-balance model is 1 metric ton of glass melt at the furnace outlet. This basis must be distinguished from a ton of dry batch and from a ton of saleable finished product. The denominators and system boundaries of the supplied scenario indicators are not independently documented, so their relative changes are interpreted only within the dataset.

2.2. Raw batch fractions and oxide balances

Let m_i denote the dry mass of ingredient i , and let x_i denote its fraction of the total dry batch:

$$x_i = \frac{m_i}{\sum_i m_i}, \quad \sum_i x_i = 1, \quad x_i \geq 0. \quad (1)$$

Raw ingredient fractions cannot be equated directly with final glass oxide fractions because carbonate-containing ingredients release gas during conversion. Define S_i as the retained glass-forming mass per unit mass of ingredient i . The batch-to-glass yield and ingredient requirement for 1 metric ton of melt are then

$$Y = \sum_i S_i x_i, \quad m_i = \frac{1000x_i}{Y}. \quad (2)$$

Here, m_i is expressed in kilograms per metric ton of glass. The idealized balance excludes dust carryover and volatilization; a plant-specific calculation must incorporate measured losses.

Table 1. Idealized oxide yields and carbonate-related CO₂ release factors.

Feed component	Retained glass-forming contribution	Retained yield, $\backslash(s_i\backslash)$ (kg/kg feed)	CO ₂ release factor, $\backslash(\delta_i\backslash)$ (kg/kg feed)
Pure silica, SiO ₂	SiO ₂	1.000	0
Sodium carbonate, Na ₂ CO ₃	Na ₂ O equivalent	0.585	0.415
Calcium carbonate, CaCO ₃	CaO equivalent	0.560	0.440
Magnesium carbonate, MgCO ₃	MgO equivalent	0.478	0.522
Clean, compatible cullet	Assayed mixture of glass-forming oxides	1.000	0

Let a_{ji} denote the retained mass of oxide j supplied by a unit mass of ingredient i . The oxide fraction in the final glass is

$$z_j = \frac{\sum_i a_{ji} x_i}{Y}, \quad z_{j,\min} \leq z_j \leq z_{j,\max}. \quad (3)$$

The bounds must correspond to a defined product rather than an unspecified glass category. For cullet, the coefficients $a_{j,c}$ should come from chemical analysis of the recycled stream. Increasing cullet content may require adjustments to several virgin ingredients.

Two cullet fractions also need to be distinguished. Its fraction of the dry batch is x_c , whereas its contribution to final glass mass is $r=x_c/Y$ under the idealized balance. These fractions differ because the virgin batch loses mass during conversion. The percentages in the supplied

dataset are retained as nominal labels; neither basis is assigned to them without supporting information.

2.3. Energy and carbon dioxide accounting

Theoretical heat demand and measured furnace energy consumption describe different quantities. Theoretical demand includes the net enthalpy change from the incoming materials to the glass and evolved gases, including heating, moisture removal, and chemical conversion. Actual energy use also depends on heat losses, exhaust conditions, heat recovery, throughput, and furnace operation. Summing isolated carbonate decomposition enthalpies is therefore insufficient to predict total furnace consumption.

For a stated furnace boundary, delivered energy can be expressed as

$$E_{\text{site}} = E_{\text{fuel}} + 0.0036W_{\text{el}}, \quad (4)$$

where E_{fuel} is fuel input in GJ per metric ton of glass on a stated heating-value basis, and W_{el} is electricity use in kWh per metric ton. Equation (4) expresses delivered energy and does not account for upstream electricity-generation losses. Theoretical heat requirements should be calculated separately and compared with metered consumption.

Direct CO₂ emissions can be separated into carbonate-related and fuel-related contributions:

$$G_{direct} = 10^{-3} \sum_i m_i \delta_i \alpha_i + EF_{fuel} E_{fuel}, \quad (5)$$

where G_{direct} is in metric tons of CO₂ per metric ton of glass, δ_i is the carbonate release factor, α_i is the reacted fraction, and EF_{fuel} is in metric tons of CO₂ per GJ. The factor 10^{-3} converts kilograms of CO₂ to metric tons.

Complete carbonate conversion, $\alpha_i = 1$, is assumed for the idealized yields in Table 1. The emissions model distinguishes process and combustion contributions [10]. Purchased-electricity emissions can be included as $EF_{el} W_{el}$, using a compatible electricity emission factor. Collection, sorting, transport, and virgin material production belong to a broader supply-chain boundary and should be reported separately when included. Recycling credits must not be combined with direct emissions without an explicit accounting rule.

2.4. Economic objective

A consistent cost model should include the material and operating expenses affected by the formulation:

$$C = \sum_i \frac{p_i m_i}{1000} + p_{fuel} E_{fuel} + p_{el} W_{el} + C_{prep} + C_{quality}. \quad (6)$$

Here, p_i is ingredient price in USD per metric ton, p_{fuel} is fuel price in USD/GJ, and p_{el} is electricity price in USD/kWh. The terms C_{prep} and $C_{quality}$ represent additional cullet preparation and quality-related costs per metric ton of glass. Preparation costs already included in the delivered cullet price must not be counted again.

Quality-related costs may include inspection, reprocessing, and rejected output where plant records support their estimation. The supplied costs cannot be assumed to include these components because their breakdown is unavailable. They are used only as scenario indicators.

2.5. Rheological and quality constraints

For a composition within an appropriate calibration domain, viscosity may be described using the Vogel–Fulcher–Tammann relationship:

$$\log_{10} \left(\frac{\eta}{1 \text{ Pas}} \right) = A + \frac{B}{T - T_0}, \quad T > T_0. \quad (7)$$

The parameters A , B , and T_0 depend on glass composition and require calibration or selection from a suitable property model. Temperature and the temperature parameters are expressed in kelvin. Viscosity units must remain consistent when using literature data [8].

At a given temperature, a homogeneous glass melt with unchanged oxide composition should not be assigned a different equilibrium viscosity solely because more of its feed originated as cullet. Cullet can affect batch conversion, while a viscosity change requires a corresponding change in glass composition or state.

Feasibility also requires adequate silica dissolution and fining within the available residence time, acceptable crystallization risk, and compliance with optical and chemical specifications. Iron limits must reflect the intended product and color. Because batch conversion depends on thermal history, temperature constraints should be assessed together with residence time and feed properties [6,7]. Numerical limits are not assigned here without product or furnace data.

2.6. Optimization framework and scenario calculations

The proposed decision variables are batch composition x , operating temperature T , and residence time τ . The multiobjective problem is formulated as

$$\min_{x, T, \tau} \{E_{site}, G_{direct}, C\}, \quad (8)$$

subject to oxide balances, ingredient availability, viscosity requirements, and product-quality constraints. Temperature is treated as an operating variable whose admissible range depends on conversion and quality requirements.

For minimization objectives, a feasible formulation dominates another when it has no higher value for any objective and a lower value for at least one. A Pareto set contains feasible, nondominated formulations. Multiple scenarios with monotonically improving indicators do not automatically constitute a Pareto front.

NSGA-II provides an established approach for searching a calibrated multiobjective problem [11]. It is identified here as a possible computational implementation; no NSGA-II run or algorithm-generated Pareto front is reported. Monte Carlo analysis is likewise a potential extension for measured feedstock variability. Without distributions, correlations, and calibrated response models, numerical uncertainty intervals are not assigned.

The present quantitative analysis consists of arithmetic comparisons of the supplied scenarios. Reductions relative to the zero-cullet reference are calculated as

$$R_F(c) = \frac{F(0) - F(c)}{F(0)} \times 100, \quad (9)$$

where $\backslash(F)$ is an indicator for which a lower value is preferred. Temperature differences are expressed in degrees Celsius. No statistical significance tests are performed because repeated measurements are unavailable.

3. Results

3.1. Comparison of the supplied scenarios

Table 2 presents the five illustrative inputs. Their values are not outputs calculated from Equations (1)–(8).

Table 2. Supplied illustrative scenarios for evaluating nominal cullet content.

Nominal cullet content (%)	Listed temperature (°C)	Energy indicator (GJ/t)	CO ₂ indicator (t CO ₂ /t)	Cost indicator (USD/t)
0	1500	5.5	0.95	100
20	1460	5.0	0.88	95
40	1420	4.5	0.80	92
60	1380	4.0	0.73	90
80	1360	3.8	0.70	89

Between the zero-cullet and 60% scenarios, the energy indicator decreases by 1.5 GJ/t, equivalent to 27.3%. The CO₂ indicator decreases by 0.22 t/t, or 23.2%, and the cost indicator falls by 10.0%. The listed temperature is 120 °C lower.

The 80% scenario has lower values for every listed indicator. Relative to the zero-cullet reference, the reductions are 30.9% for energy, 26.3% for CO₂, and 11.0% for cost. These calculations describe the supplied scenarios; they do not demonstrate achievable furnace performance.

3.2. Incremental benefits

The energy indicator decreases by 0.5 GJ/t for each 20-percentage-point increase between 0 and 60% cullet. The corresponding decrease from 60 to 80% is 0.2 GJ/t. The temperature indicator follows a similar pattern, falling by 40 °C in each of the first three intervals and by 20 °C in the final interval.

The absolute CO₂ decreases across the four intervals are 0.07, 0.08, 0.07, and 0.03 t/t. Cost reductions are 5, 3, 2, and 1 USD/t. Thus, the last interval provides smaller additional improvements, especially for energy and emissions. However, energy and temperature values are linear across the first four scenarios. The dataset does not establish a strongly nonlinear relationship over the entire range.

Using the 60% scenario as the reference, moving to 80% corresponds to further reductions of 5.0% in energy, 4.1% in CO₂, and 1.1% in cost. Smaller marginal benefits do not, by themselves, establish an interior optimum.

3.3. Dominance analysis and the proposed operating range

When quality feasibility is left unassessed, the 80% scenario dominates all four lower-cullet scenarios for the listed minimization objectives. Including the temperature indicator does not change this ranking. The supplied data therefore contain no demonstrated conflict between energy, emissions, and cost.

A 50–65% optimal range cannot be inferred from these five inputs. Neither endpoint is evaluated, and no quality metric establishes a constraint that excludes the 80% scenario. Likewise, a general loss of homogeneity above 70% is not demonstrated. Establishing such a limit would require measured changes in composition consistency, undissolved inclusions, bubble content, color, or other product-specific properties.

The result of the dominance analysis is therefore conditional: the highest listed cullet scenario is preferred by the supplied objective values, while its physical and product-quality feasibility remains unresolved.

3.4. Analytical implications of the mass balance

The oxide balance yields a direct relationship between cullet composition variability and final glass chemistry. For a fixed recipe, with unchanged cullet retained yield and unchanged contributions from the other ingredients,

$$\Delta z_j = \frac{x_c}{Y} \Delta a_{j,c} = r \Delta a_{j,c}. \quad (10)$$

Here, $\Delta a_{j,c}$ is a change in the oxide fraction of the cullet, and Δz_j is the resulting change in final glass composition. This is an analytical sensitivity relationship, not a Monte Carlo result. It shows that greater reliance on cullet transfers a larger fraction of recycled-feed composition variability to the product unless the virgin recipe is adjusted.

A second relationship follows for clean, composition-matched cullet. If the target oxide composition remains

fixed and the virgin recipe is scaled proportionally, carbonate-derived emissions per metric ton of glass satisfy the idealized expression

$$G_{\text{process}}(r) = (1-r)G_{\text{process}}(0). \quad (11)$$

This result applies to carbonate-related emissions under the stated substitution assumptions. It does not describe fuel consumption or total emissions, and it is not fitted to Table 2. The two relationships explain why cullet selection requires both material substitution accounting and feedstock quality control.

4. Discussion

4.1. Energy savings and the meaning of temperature

Cullet can reduce the virgin batch conversion requirement, but the size of a furnace energy saving depends on operating conditions. Lower reaction demand does not eliminate the energy required to heat the glass or compensate for furnace losses. Throughput, heat recovery, and feed preparation must therefore be considered when transferring a formulation result to production.

The magnitude of the supplied energy reduction requires particular caution. AGC Glass Europe reports an approximate 2.5% reduction in furnace energy consumption for a 10% increase in cullet use [12]. A simple extrapolation over a 60-percentage-point increase would give approximately 15%, compared with 27.3% in Table 2. This comparison is only indicative because the glass type, percentage basis, furnace boundary, and operating conditions may differ. It shows that the supplied saving needs an explanation and supporting measurements.

The listed temperatures also require interpretation. A processing temperature is not an intrinsic melting point for glass. At unchanged final chemistry, cullet may alter how quickly a batch converts without producing the same change in the temperature associated with a specified melt viscosity. Deng et al. found that theoretical batch energy requirements were not determined by melting temperature alone in their analyzed compositions [4]. Temperature, conversion kinetics, and total energy should consequently remain distinct assessment quantities.

4.2. Cullet quality and feasible recycled content

The usable cullet fraction depends on its compatibility with the intended glass. Composition variation can be corrected only within the adjustment capacity of the remaining ingredients. Equation (10) makes this dependence explicit: increasing recycled content increases the influence of cullet chemistry on the final oxide balance.

Physical preparation introduces another constraint. Deng et al. demonstrated that briquetting cullet fines could permit their addition to a representative container batch while maintaining comparable composition and optical characteristics after suitable recipe adjustment [13]. Their results support evaluating particle form and preparation rather than treating all recycled glass as an interchangeable input. The melting study of the briquetted feed also supports attention to reaction kinetics [5].

There is no general basis for assigning 70% as a threshold for melt instability. The commercial glass survey reports that some container-glass streams can use cullet fractions exceeding 90%, while suitability depends on the product and recycled-feed purity [4]. A plant with clean, composition-compatible cullet may therefore accept a higher recycled fraction than one dependent on a variable external supply.

In the proposed framework, the feasible range is defined by assayed feed chemistry and demonstrated product compliance. It cannot be set by diminishing energy savings alone. A formulation with lower energy demand remains unsuitable if it fails a required quality constraint.

4.3. Economic trade-offs and multiobjective selection

Multiobjective optimization becomes useful when feasible formulations have conflicting consequences. Greater cullet use may reduce virgin material and energy requirements while increasing sorting, inspection, or supply costs. A change in oxide chemistry may improve processing behavior while approaching a durability or optical limit. Such conflicts must be represented by measured or calibrated responses.

Table 2 does not contain those conflicts: all listed indicators favor the same scenario. Its diminishing cost savings suggest that additional benefits become smaller,

but the positive direction remains unchanged. Assigning an intermediate optimum would require a binding constraint or an additional cost that reverses the ranking.

A numerical optimizer can search only the problem defined by its inputs. NSGA-II cannot establish an industrially valid optimum if its energy, emission, and quality responses have not been calibrated. For the five supplied scenarios, direct dominance comparisons are sufficient; an evolutionary algorithm would add no evidence.

4.4. Uncertainty and batch correction

Feedstock variability should be connected to observable formulation requirements. Cullet oxide assays, moisture, contamination, and delivered price can vary between lots. Equation (10) provides a first assessment of chemistry sensitivity, but it assumes fixed yield and unchanged contributions from the other ingredients. If contaminants change retained yield, the complete oxide balance must be reevaluated.

Where adequate data exist, Monte Carlo sampling can propagate jointly observed variations through calibrated response models. Oxide fractions must remain compositionally consistent, and correlated variations should not be replaced by independent draws without justification. Reporting a sampling method without these inputs would not establish robustness.

A practical application of the framework would use updated feed analyses to calculate the remaining virgin ingredient requirements, followed by checks against composition and operating limits. Automated batch correction would require demonstrated model accuracy and reliable measurements before deployment.

4.5. Limitations and validation requirements

The quantitative analysis is limited to five undocumented illustrative scenarios. It contains no measured final oxide compositions, viscosity curves, defect counts, residence times, or uncertainty estimates. Consequently, the numerical savings cannot be attributed solely to cullet substitution, and the proposed formulation framework has not been experimentally validated.

Validation requires a defined product and reference recipe, chemical analyses of all feed streams, and a

documented cullet percentage basis. Furnace trials should compare formulations under recorded throughput, thermal conditions, and energy-metering boundaries. Finished glass should be assessed for the properties that determine acceptance. Carbonate-derived and fuel-derived CO₂ should be calculated separately, while costs should use consistent delivery and processing boundaries.

These measurements would allow the framework to move from transparent formulation screening to a calibrated optimization study. They are also needed to determine whether an intermediate operating range offers a practical advantage over the highest feasible cullet content.

5. Conclusion

A composition-constrained framework has been formulated for evaluating cullet use in soda–lime–silica glass batches. It distinguishes dry batch fractions from final oxide fractions, separates process and fuel emissions, and treats melt quality as a requirement for feasible formulation selection.

The supplied illustrative scenarios associate a nominal increase from 0 to 60% cullet with reductions of 27.3% in energy, 23.2% in CO₂, and 10.0% in cost. Additional benefits between 60 and 80% are smaller, but the 80% scenario remains preferable for every listed minimization objective. The dataset therefore supports neither a 50–65% optimum nor an algorithm-generated Pareto front.

The analytical balances show that clean, composition-matched cullet can reduce carbonate-derived emissions in proportion to its contribution to final glass mass. They also show that increased cullet use strengthens the dependence of final oxide composition on recycled-feed chemistry. These relationships support evaluating recycled content together with feed characterization and recipe correction.

The appropriate cullet range must be established for a specified product, supply stream, and furnace. Plant measurements and quality validation are required before the scenario values or proposed framework can support an industrial performance claim.

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