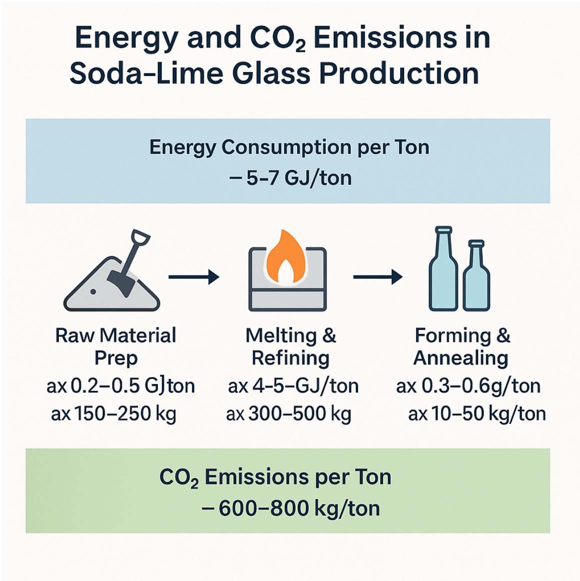
Energy Requirements and CO_2 Emissions in Soda-Lime (Silicate) Glass Production

Energy Demand for Glass Production

Commercial **soda-lime silicate glass** manufacturing is highly energy-intensive. Recent analyses indicate that producing 1 ton of glass typically requires on the order of **5–7 GJ/ton** of energy (approximately **1,400–1,940 kWh/ton**) in modern large-scale facilities . This figure represents the total energy from raw materials through melting and forming. For example, one case study with furnace upgrades reported an energy intensity reduction from about **1,340 kWh/ton to 1,304 kWh/ton** of glass – illustrating a **total energy demand around 1.3–1.4 MWh per ton** in that plant. For context, the *theoretical minimum* energy to melt silica-based glass (at ~1,500 °C) is roughly **2.8–3.0 GJ/ton** , but in practice actual consumption is much higher due to heat losses and process inefficiencies.



Breakdown by production stage: The **melting furnace** dominates energy usage, whereas raw material preparation and finishing consume comparatively less:

- **Raw material mining & preparation:** Extracting and preparing raw materials (silica sand, limestone, soda ash, etc.), including transport and batch mixing, accounts for a relatively small fraction of the energy. A U.S. DOE report noted that **batch preparation is only ~4%** of a glass plant's total energy use . In absolute terms this stage typically consumes on the order of **10^2 kWh per ton** (hundreds of kWh). For instance, *materials handling* for container glass can be ~0.5×10^6 Btu/ton (≈155 kWh/ton) . Mining and crushing of sand/limestone require additional energy (often tens of kWh), but remain minor compared to melting. *Upstream chemical processing* can be significant for certain inputs – notably **soda ash** (sodium carbonate) manufacturing. The Solvay process for soda ash consumes **~9.7–13.6 GJ per ton of Na_2CO_3** (about 2.7–3.8 MWh/ton), meaning the ~0.2 ton of soda ash used per ton of glass carries an embedded energy of ~2 GJ. (However, much of soda ash's chemical energy is released in the melting furnace itself as CO_2, discussed below.) Overall, **raw material acquisition and batch prep typically contribute well under 20% of total energy** in glass production.
- **Melting and refining:** The **glass melting furnace** is by far the largest energy consumer, often responsible for **~70–80% of the total energy input** . In a continuous regenerative furnace (common in float and container glass plants), fuel combustion provides the high heat to melt the batch at ~1,500 °C. In modern operations this stage usually requires roughly **3.5–5 GJ/ton** (≈ **1,000–1,400 kWh/ton**) of energy input for a soda-lime glass melt . (One industry source notes **≈4 GJ/ton (1.1 MWh/ton)** as a

typical figure for fossil-fuel-fired furnaces .) Most of this energy (~40%) actually goes into heating and chemically reacting the batch, while the rest is lost as waste heat – roughly **30% lost via the furnace structure and ~30% in hot flue gases** in older designs . Advanced heat-recovery (regenerative or recuperative furnaces), electric boosting, and better insulation have improved furnace efficiency over time. Today, state-of-the-art **oxy-fuel or electric furnaces** can reduce melting energy to as low as ~**2.6–2.8 GJ/ton** (0.72–0.78 MWh) under ideal conditions , especially with high cullet (recycled glass) use. In practice, large float-glass furnaces (making flat glass) and container-glass furnaces will have energy intensities in the mid-single-digit GJ/ton range. **Melting remains the primary energy hotspot**, since large volumes of material must be heated to high temperature and the endothermic decomposition of carbonates also consumes energy.

- **Forming, annealing, and post-processing:** Once molten glass is refined, it is formed into products (e.g. floated into sheets, blown into bottles) and then cooled under controlled conditions (annealing). These downstream steps consume the remainder (~15–25%) of the energy. Most forming/finishing energy is for **equipment and temperature control** rather than intensive heating. For example, **container glass forming** (blowing bottles, operating molding machines, powering compressors for air blow) uses on the order of **100–150 kWh/ton** . A 1990s survey found container forming accounted for ~12% of total energy, whereas in glass fiber production forming could reach ~34% . **Annealing lehrs** (ovens that slowly cool the glass to relieve stress) also require energy, often fired by natural gas or electricity. In flat-glass plants, the continuous annealing lehr plus any bath heaters for the float process can consume a few hundred kWh per ton. (One EPD for float glass indicates higher forming energy – e.g. **~440 kWh/ton** for flat glass forming , versus ~105 kWh/ton for container glass – reflecting the extended float bath and lehr heating in flat glass.) In summary, **forming and annealing** generally use **<< 1 GJ/ton** (a few hundred kWh at most) in modern facilities . This is much less than the melting stage, and a portion is often supplied by electricity (for drives, cooling fans, compressors, etc.).

Table 1 summarizes the **specific energy consumption** by stage for a representative soda-lime glass production scenario (virgin batch, minimal cullet). (Note that actual values vary with furnace technology, cullet use, and product type.)

Table 1 – Typical Energy Use by Production Stage (per 1 ton soda-lime glass)

Stage	Energy Consumption	Share of Total Energy
Raw material prep (mining, transport, batch mixing)	~**0.2–0.5 GJ/ton** (≈50–150 kWh) *Relatively small – e.g. ~4% of total .*	~5–15% *(generally minor)*
Melting & refining (furnace)	~**4–5 GJ/ton** (≈1,100–1,400 kWh) *High-temperature furnace fuel input; largest energy component.*	~70–80% *(majority)*
Forming & annealing (shaping, cooling)	~**0.3–0.6 GJ/ton** (≈80–160 kWh) *Machine drives, compressors, annealing ovens (some fuel or electric heat).*	~10–20% *(moderate)*
Total (entire process, virgin materials)	**~5–7 GJ/ton** (≈1,400–1,900 kWh) *Typical modern plant total energy per ton.*	100%

(Energy values are approximate; actual values depend on furnace efficiency, cullet %, etc. Higher cullet use can reduce melting energy significantly.)

In terms of **energy sources**, most glass plants rely on **fossil fuels (natural gas, fuel oil)** for melting heat, with electricity providing a smaller portion. On average about **75–80% of the energy comes from fuel combustion and ~20–25% from electricity** in glass manufacturing . This balance is gradually shifting as technologies like electric boosting and all-electric furnaces are adopted for decarbonization, but as of the late 2010s, gas-fired furnaces remain standard. For instance, all AGC Glass Europe furnaces transitioned from heavy oil to natural gas over the past decades for efficiency and emission benefits.

Impact of cullet (recycled glass): Using recycled glass cullet in the batch greatly reduces energy requirements. Cullet melts at a lower temperature than raw batch materials, directly offsetting some of the energy needed to break down raw carbonates. *Rule of thumb:* **Every 10% increase in cullet reduces melting energy by roughly 2%** . Industrial data confirm that high cullet furnaces operate at the lower end of energy intensity. (In one trial, an **88% cullet** mix plus preheating cut fuel usage substantially .) Thus, a plant making glass **from 100% recycled cullet** might use on the order of **3–4 GJ/ton** instead of 5–7 GJ/ton, demonstrating how upstream energy (and emissions) can be avoided by recycling.

CO_2 Emissions per Ton of Glass

Glass manufacturing is not only energy-intensive – it is also **carbon-intensive** due to combustion of fossil fuels and the raw materials themselves. The **CO_2 emissions** associated with producing 1 ton of soda-lime glass are typically in the range of **0.6 to 0.8 metric tons of CO_2 per ton of glass** produced . In other words, **600–800 kg CO_2 per ton** is a representative emission intensity for modern glass production using mostly virgin raw materials. This is a *cradle-to-gate* figure including direct process emissions and energy use on-site (often reported as "Scope 1+2" emissions for the plant). Some recent industry benchmarks in Europe are a bit lower thanks to efficiency improvements and cleaner energy – for example, one glassmaker reports **~0.436 t CO_2/ton** as of a few years ago , and another's 2019 average was **0.523 t CO_2/ton** . These lower values reflect high cullet usage, efficient furnaces, and greener electricity. By contrast, facilities with older technology or coal-based fuel can exceed 0.8 t CO_2/ton (the **global average** has been estimated around *0.8–1.0 t CO_2/ton* historically , and one "rest of world" model yields ~1.65 kg CO_2/kg , though this likely assumes coal-heavy energy).

Sources of emissions: Crucially, the CO_2 emissions in glassmaking come from **two main sources**:

- **Fuel combustion (energy-related CO_2):** Burning natural gas (or other fuels) in the furnace generates CO_2. This is typically the largest contributor. According to industry data, **about 75% of the direct CO_2 emissions from a glass furnace are due to fuel combustion** . For a ton of glass, this corresponds to roughly **300–500 kg CO_2** just from burning fuel (depending on the fuel type and amount). For example, Beta Glass PLC (a container glass manufacturer) had baseline emissions around **520 kg CO_2/ton**, mostly from natural gas combustion, before recent upgrades . Improving furnace efficiency (and adding electric boost) at that plant cut emissions by ~10%, down to **≈453 kg CO_2/ton** . The combustion CO_2 scales with energy use – roughly **55 kg CO_2**

per GJ for natural gas (or ~200 kg CO_2 per MWh), so a furnace using ~4 GJ/ton (~1100 kWh) of gas would emit ~220 kg from fuel, whereas 6 GJ/ton would emit ~330 kg from fuel. (Heavier fuels like oil or coal would emit more per unit energy.) Notably, **electricity-related CO_2** (from grid power used in forming, etc.) is usually much smaller – on the order of tens of kg CO_2/ton – and is often counted in Scope 2 emissions. In France, for instance, grid electricity is low-carbon (nuclear), so *most* CO_2 comes directly from gas; in regions with coal-fired power, the balance differs.

- **Process CO_2 (carbonate decomposition):** Soda-lime glass raw materials include **carbonate compounds** (soda ash = Na_2CO_3, limestone = $CaCO_3$, dolomite, etc.). During melting, these carbonates **decompose (decarbonation)**, releasing CO_2 gas. This chemical release is **pure CO_2** from the raw ingredients and does not come from fuel. It is often termed *process* or *raw material* CO_2. Roughly **20–25% of glass CO_2 emissions are from raw material decomposition** in a typical soda-lime batch . In quantitative terms, a fully virgin batch (no recycled glass) can release on the order of **0.15–0.25 t CO_2 per ton** of glass just from the CO_2 driven out of Na_2CO_3 and $CaCO_3$. For example, limestone ($CaCO_3$) and soda ash (Na_2CO_3) in one ton of glass might liberate roughly **150–200 kg CO_2** during melting (exact amount depends on glass recipe) . This is **intrinsic** to making silicate glass from those carbonates – each CO_3 group leaves as CO_2 gas. (An older analysis calculated ~168 kg of *carbon* – equivalent to ~616 kg CO_2 – released per ton, but this figure is likely assuming all carbonate sourcing including soda ash production . More recent industry data point to a lower process CO_2 fraction, ~25% of total emissions .) The key point is that using **cullet** avoids this source: recycled glass has already released its CO_2 in a previous life, so **each 10% cullet reduces raw material CO_2 by a similar ~2–3%**, on top of the energy savings .

Given these two sources, the **total CO_2/ton** is the sum of fuel CO_2 + process CO_2 (plus any indirect electricity CO_2). For a standard mix, if ~75% is fuel and 25% process , a 0.7 tCO_2/ton total would break down into ~0.525 t from fuel and ~0.175 t from raw materials. Table 2 provides an overview of typical emissions per ton and their origin:

Table 2 – Typical CO_2 Emissions in Soda-Lime Glass Production (per 1 ton glass)

Emission Source	CO_2 Emitted (kg per ton glass)	Notes
Fuel combustion (on-site energy)	**~300–500 kg** CO_2/ton 1	Burning natural gas (dominant fuel) in furnace (and lehr). Accounts for ~¾ of emissions . Efficient furnaces & cleaner fuels reduce this.
Raw material decomposition	**~150–250 kg** CO_2/ton 2	CO_2 liberated from carbonates (Na_2CO_3, $CaCO_3$) during melting. ~¼ of emissions . Nearly eliminated if using cullet (cullet undergoes no decarbonation).
Electricity use (indirect)	**Varies** (e.g. ~10–50 kg CO_2/ton)	Indirect CO_2 from power for batch prep, forming, etc. Magnitude depends on grid carbon intensity. (Can be near-zero with renewable/nuclear electricity.)
Total CO_2 per ton of glass	**~600–800 kg** CO_2/ton	Representative total (all scopes) for soda-lime glass with primarily virgin inputs. High-cullet, efficient

Emission Source	CO_2 Emitted (kg per ton glass)	Notes
		operations can be ~400–500 kg/ton ; less efficient ones can approach ~1000 kg/ton.

1Assumes ~4–6 GJ of fossil fuel energy per ton. Natural gas emits ~50–56 kg CO_2/GJ; fuel oil ~74 kg/GJ.

2If soda ash is produced via limestone calcination (Solvay process), an equivalent CO_2 release occurs at the soda plant; however, the CO_2 in the soda ash itself is released in the glass furnace.

CO_2 reduction measures: The glass industry has achieved notable emission reductions over time by improving energy efficiency and increasing cullet recycling. In France, *specific CO_2 emissions per ton of glass* have fallen significantly since the 1960s (from ~1,800 kg/ton in 1960 down to ~600–700 kg/ton by 2010) , thanks to more efficient **regenerative furnaces, use of natural gas instead of fuel oil, and higher cullet use**. Over 1990–2020, European float glass producers cut direct CO_2 emissions by ~30% through furnace upgrades and fuel shifts . Going forward, **decarbonization** efforts focus on electrified melting, hydrogen fuel trials, and alternative glass compositions. For instance, researchers are developing new “low-carbon” glass (e.g. **LionGlass**) with different chemistries that could **cut CO_2 emissions by ~50%** by reducing carbonate usage and lowering melting temperatures .

It’s worth noting that **recycling glass** provides a double benefit: it *saves energy* and *avoids raw-material CO_2*. Even accounting for collection and processing, **using cullet can save ~315 kg CO_2 per ton** of glass produced compared to all-virgin production. This is why the industry heavily promotes container glass recycling – every bottle remelted avoids mining new sand and decomposing fresh carbonates, and requires less fuel in the furnace. In practical terms, a typical glass plant in 2025 using **50% cullet** might have an energy demand of only ~4 GJ/ton and emissions perhaps **~400–500 kg CO_2/ton**, whereas a plant with minimal cullet might be at 6–7 GJ/ton and ~750 kg CO_2/ton .

Summary: Producing 1 metric ton of soda-lime silicate glass in a large-scale industrial facility requires on the order of **5–7 gigajoules** of energy (**≈1,500 kWh/ton**), mainly for high-temperature melting . This corresponds to roughly **600–800 kilograms of CO_2 emissions per ton**, assuming current typical fuel use and batch makeup . The **melting stage** is the dominant energy and CO_2 contributor, while upstream raw material processing and post-forming steps are smaller components. Table 3 recaps the typical totals for a virgin-material soda-lime glass production scenario:

Table 3 – Typical Total Energy Use and CO_2 Emissions for Soda-Lime Glass (per 1 ton)

Energy Use (GJ/ton)	Energy Use (kWh/ton)	CO_2 Emissions (kg/ton)	Notes
≈5–7 GJ/ton (total)	**≈1,400–1,900 kWh/ton**	**≈600–800 kg CO_2/ton**	Modern large-scale production with mostly virgin raw materials. High cullet content can lower both energy and CO_2 by ~10–20%.

All data are for **soda-lime silica glass**, the standard composition for bottles, jars, and float glass. Other silicate glasses (e.g. borosilicate) may have slightly different energy profiles due to different melting points and raw materials, but the same principles apply. In conclusion, *per ton of glass*, one can expect on the order of **several gigajoules of energy consumption** and **hundreds of kilograms of CO_2 emissions**, with the **melting furnace** being the key driver of both energy use and greenhouse gas emissions .

Sources: Industrial energy surveys and academic studies (post-2015) were used for the above values. For example, Cantini *et al.* (2022) report 5–7 GJ/ton as the typical energy intensity of glass manufacturing . The U.S. DOE and EPA profiles of the glass industry detail energy breakdowns by process step . Industry data from AGC Glass Europe and Beta Glass illustrate current CO_2 intensities and improvements . O-I Glass, a major bottle producer, contextualizes the carbon footprint at ~0.6–0.8 t CO_2/ton . These figures represent typical large-scale production with state-of-the-art (as of 2020s) technology and are widely used as benchmarks in both life-cycle assessments and decarbonization roadmaps for the glass sector.