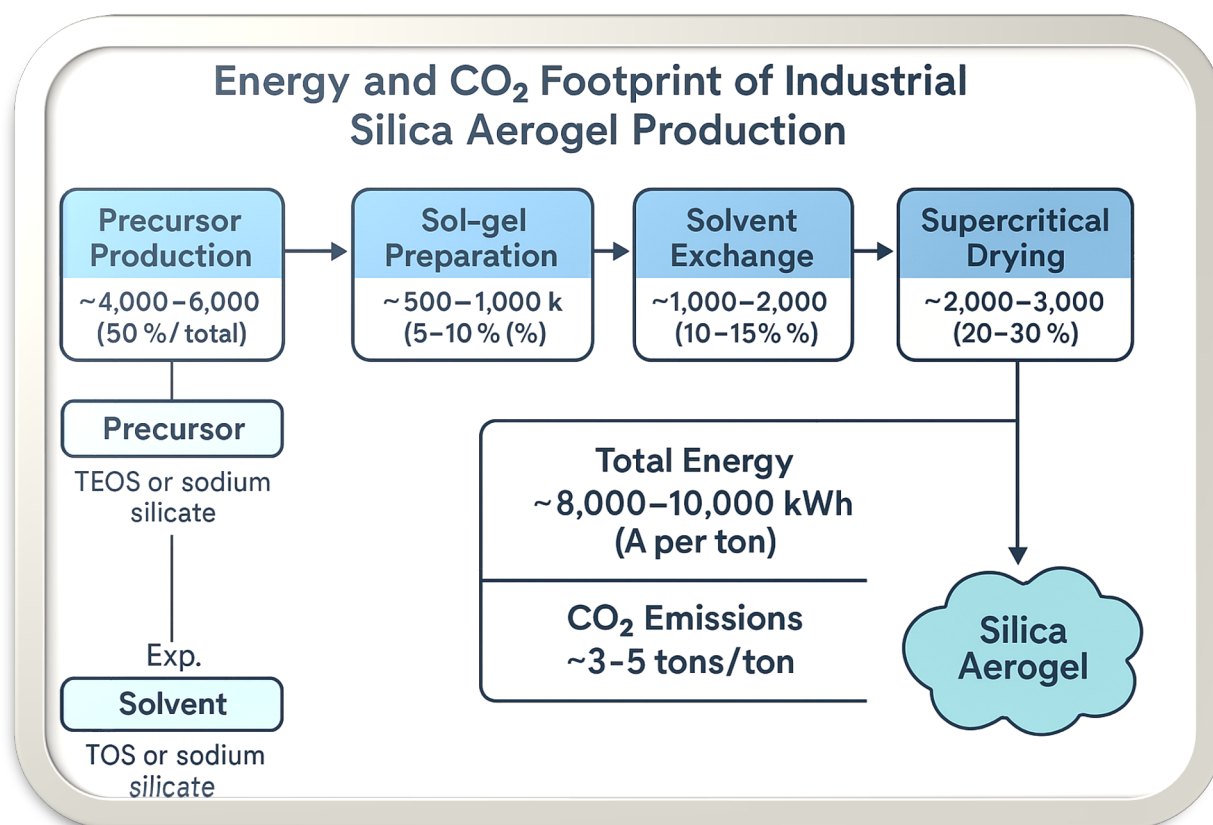




## Energy and CO<sub>2</sub> Footprint of Industrial Silica Aerogel Production

### Total Energy Requirements and Stage Breakdown

Producing silica aerogel at industrial scale is **highly energy-intensive**, primarily due to the precursor materials and the drying process. Typical total energy consumption is on the order of **tens of gigajoules per ton** of aerogel. For conventional supercritical CO<sub>2</sub>-dried silica aerogel, manufacturers report roughly **53.9 MJ per kg** of aerogel produced ( $\approx 15,000$  kWh per ton). Newer processes can reduce this significantly (down toward  $\sim 8$ – $9$  kWh/kg, or  $\sim 8,000$ – $9,000$  kWh/ton) by using alternative precursors and drying methods. Below is a breakdown of energy use by production stage for the standard supercritical drying route:



- Precursor Production:** Generating the silica precursor is often the *single largest energy sink*. Traditional aerogels use tetraethyl orthosilicate (TEOS) or similar organosilicates, whose production carries a very high energy cost and CO<sub>2</sub> footprint (e.g. high-temperature processes yielding corrosive byproducts like HCl). In one LCA, **>70% of the total environmental impact** of a TEOS-based aerogel was attributed to raw material (precursor) production. Switching to sodium silicate (“water glass”) can cut this down – it is cheaper and avoids halogenated byproducts – *but* water glass itself is made by melting sand and soda at  $\sim 1300$ – $1600$  °C, consuming substantial energy and emitting CO<sub>2</sub>. (Using waste glass or bio-sourced silica can mitigate precursor energy by  $\sim 20$ – $30\%$ .) In



quantitative terms, producing the precursor may account for **several thousand kWh per ton** of aerogel – on the order of 5,000–10,000 kWh/ton for TEOS-based processes (the high end for TEOS, lower for water-glass routes).

- **Sol–Gel Preparation and Aging:** Forming the silica sol (hydrolysis/condensation) and allowing the gel network to strengthen (aging) require **mixing, reaction, and sometimes mild heating** but are relatively minor energy contributors compared to precursor and drying steps. Gelation is often done near room temperature or slightly elevated temperature (with stirring). Even when heating is needed (e.g. to dissolve a silica source or catalyze gelation), the energy is modest on an industrial scale. For example, heating a *lab-scale* 0.5 L silica mixture took ~2.2 kWh, whereas a **100 L batch** needed only ~14.6 kWh (greatly improved per-unit efficiency). Aging the gel (often for hours or days) typically occurs at ambient or moderate temperature, so energy input is mainly for maintaining temperature (which can be as low as room temperature or ~50 °C). **Overall, gelation+aging might contribute on the order of a few hundred kWh per ton** of product (only a few percent of the total energy).
- **Solvent Exchange:** After gelation, the **wet gel (hydrogel)** must be exchanged to a solvent suitable for drying. This involves multiple wash/soak steps (e.g. replacing water with methanol or ethanol, then possibly with liquid CO<sub>2</sub>). The direct energy for pumping and stirring these large solvent volumes is moderate. However, if solvents are **recovered via distillation** for reuse, that distillation can add a significant energy cost. In industrial practice, solvent exchange energy is still smaller than drying energy, but not negligible – roughly **10–20% of the process energy** may be tied up in heating/pumping for solvent exchange and solvent recovery operations. (For instance, an ambient-pressure process with multiple exchanges reported several heating steps contributing a few kWh per batch.) Efficient solvent recycling (e.g. using waste heat for distillation) can reduce the net energy here.
- **Supercritical Drying:** The **drying stage** is notoriously energy-intensive. In the standard process, the solvent-filled gel (alcogel) is loaded into an autoclave and dried above the solvent's critical point to avoid pore collapse. **Supercritical CO<sub>2</sub> drying (SCD)** is most common in modern production – after exchanging the pore liquid with CO<sub>2</sub>, the autoclave is heated to ~40–50 °C and pressurized ~100 bar to take CO<sub>2</sub> supercritical, then CO<sub>2</sub> is vented. This requires energy for **pressurizing and heating** the autoclave and for **circulating and recovering CO<sub>2</sub>**. In practice, the supercritical drying step can account for on the order of **1,000–3,000 kWh per ton** of aerogel (roughly 10–20% of total energy in a TEOS-based process). For example, lab measurements of a CO<sub>2</sub> dryer show a few kWh of electricity per small batch (e.g. ~3.1 kWh to dry a liter-scale autoclave load). At industrial scale, multiple gels are dried in one autoclave cycle, so the **per-kilogram energy** is lower. Still, heating the CO<sub>2</sub> and vessel, plus compressing CO<sub>2</sub>, is a major energy draw. *Ambient-pressure drying* avoids high-pressure autoclaves (see comparison below), but it still demands energy to evaporate large solvent quantities. In summary, **drying (whether SCD or ambient)** is a major consumer of energy, alongside precursor synthesis.



**Table 1** below summarizes a representative energy breakdown for an industrial-scale silica aerogel process (supercritical CO<sub>2</sub> drying, using a conventional silica precursor). This assumes a sodium-silicate-based process (for a TEOS-based route, the precursor energy share would be even higher).

Process Stage	Approx. Energy (kWh/ton)	Share of Total (%)
Precursor production	~4,000–6,000	~50% or more
Sol-gel mixing & aging	~500–1,000	~5–10%
Solvent exchanges & prep	~1,000–2,000	~10–15%
Supercritical drying	~2,000–3,000	~20–30%
<b>Total (SCD process)</b>	<b>~8,000–10,000</b>	<b>100%</b>

*Table 1: Estimated energy consumption by stage for silica aerogel production via supercritical CO<sub>2</sub> drying (per ton of finished aerogel). Actual values vary with process specifics; TEOS-based processes tend toward the higher end of energy use (total ~15,000 kWh/ton) , while waterglass-based or waste-derived silica routes tend toward the lower end .*

## CO<sub>2</sub> Emissions per Ton of Aerogel

The carbon footprint of silica aerogel production is similarly large. A *typical value* reported by manufacturers is about **4.3 kg CO<sub>2</sub> per kg of aerogel** (i.e. ~4.3 tons CO<sub>2</sub> per ton) . This figure, from Aspen Aerogels' data for a supercritical CO<sub>2</sub>-dried blanket, excludes the CO<sub>2</sub> used as the drying medium (since in their process that CO<sub>2</sub> is recycled from other industrial processes) . Major contributors to emissions are the same as for energy: the production of precursors (e.g. producing TEOS or sodium silicate releases CO<sub>2</sub> from high-temperature furnace operations ) and the consumption of electricity/heat for drying. For TEOS-based processes, the **preponderance of CO<sub>2</sub> emissions comes from making the precursor** – one study found *raw material production* dominated global warming potential for TEOS aerogel, again >70% of the total . Using sodium silicate or recycled glass as silica source can cut total CO<sub>2</sub> per kg aerogel by roughly **20–30%** , both by reducing process energy and avoiding emissions from organosilicate synthesis.

In practice, current commercial aerogel production (supercritical drying, with a mix of grid power and fossil-based heat) will emit on the order of **3–5 tons CO<sub>2</sub> per ton** of aerogel. For example, the ~15 kWh/kg energy figure above corresponds to ~4–5 kg CO<sub>2</sub>/kg assuming typical electricity sources. In a recent analysis of an optimized ambient-pressure process, the authors obtained **8.45 kWh/kg and ~8.15 kWh/kg** for scaled-up production, and reported that the **kg CO<sub>2</sub> per kg** was essentially on par with supercritical drying methods . (Using cleaner energy sources can of course improve the emissions: e.g. sourcing electricity from renewables or utilizing waste heat could substantially lower the CO<sub>2</sub> per ton without changing the process steps.)



## Supercritical vs. Ambient Pressure Drying (Energy & Emissions)

**Supercritical CO<sub>2</sub> drying (SCD)** has long been the standard for silica aerogel manufacture, but **ambient pressure drying (APD)** methods have been developed to avoid the cost and hazard of high-pressure autoclaves. One might expect APD to save energy, but in practice *both methods have significant energy requirements*, just in different forms. Recent LCA studies indicate that **well-optimized APD processes can have similar energy usage and environmental impact to SCD**.

In ambient pressure drying, the wet gel is chemically surface-modified (silylated) to strengthen it, then the solvent is evaporated by heating at atmospheric pressure (often in an oven). This avoids compressing CO<sub>2</sub> to supercritical conditions, but instead **all the pore solvent must be vaporized**, which requires a large heat input (latent heat). For instance, evaporating ~9–10 kg of ethanol per kg of aerogel might demand on the order of 2–3 kWh/kg just in vaporization heat. In one study of an APD process (using waste glass precursor), the **drying stage** consumed ~3.6 kWh for a 0.5 L lab batch and ~10.5 kWh for a 100 L (model) batch. At industrial scale this was only ~0.2 kWh per kg (thanks to heat recovery and batch size) – a small fraction of the total. However, APD required multiple solvent exchanges and the use of hydrophobizing agents (e.g. HMDS), which introduced other energy and material costs. Ultimately, the **total energy per kg** came out to **8–9 kWh/kg in the APD case**, very comparable to supercritical drying routes. Similarly, **CO<sub>2</sub> emissions per kg** were found to be *not significantly different* between APD and SCD in that analysis.

**Table 2** provides a side-by-side comparison of typical energy and CO<sub>2</sub> metrics for supercritical vs ambient drying routes. (These assume modern processes using sodium silicate or similar silicate precursors, at industrial scale. TEOS-based SCD would be higher in both energy and emissions.)

Process	Total Energy (kWh/ton)	CO <sub>2</sub> Emissions (kg/ton)
Supercritical CO <sub>2</sub> drying	~10,000–15,000 <sup>a</sup>	~4 × 10 <sup>3</sup> – 5 × 10 <sup>3</sup>
Ambient pressure drying	~8,000–10,000 <sup>b</sup>	~3 × 10 <sup>3</sup> – 5 × 10 <sup>3</sup>

<sup>a</sup> Lower end for water-glass based process; upper end for TEOS-based.

<sup>b</sup> Assumes efficient heat recovery; based on waste-glass APD pilot data.

Both methods consume on the order of **10<sup>4</sup> kWh per ton** of product, and emit a few **thousand kg of CO<sub>2</sub> per ton**. The key advantage of ambient drying is less specialized equipment (no high-pressure vessel), rather than a dramatic reduction in energy use. In fact, all drying methods for aerogels are somewhat costly: *freeze-drying*, for example, avoids solvents but typically has **even higher energy consumption** unless done with highly efficient, large-scale equipment. Thus, ongoing research is focused on **reducing energy**



**demand** in all stages – for example, using cheaper precursors (or waste sources of silica), recycling solvents and waste heat, and employing faster drying techniques – to bring down the embedded energy and emissions of aerogel production .

Overall, producing 1 ton of silica aerogel via current supercritical drying methods typically requires on the order of **50 GJ of energy per ton ( $\approx 15,000$  kWh/ton)** of product . Breaking this down by stage, a large portion (half or more) comes from making the silica precursors, with the supercritical drying step itself often accounting for 10–30%. Thanks to process optimizations, **industrial-scale systems are far more efficient** (per kg) than lab-scale trials – e.g. one study saw energy drop from *519 kWh/kg at lab scale* to  *$\sim 8.2$  kWh/kg at 1000 L scale* . The associated carbon emissions are on the order of **4 ton CO<sub>2</sub> per ton** of aerogel for the standard process , with similar figures observed for emerging ambient-pressure processes . Table 2 highlights that switching to ambient drying is *not* a panacea for energy/emissions – both routes have comparable footprints unless low-carbon energy sources are used. Therefore, any commercial aerogel production must carefully manage energy use in **each step – from raw materials to drying** – to improve sustainability.

**Sources:** Modern LCA studies and manufacturer data for silica aerogels . The values reported (post-2015) are from industrial or pilot-scale analyses, comparing supercritical CO<sub>2</sub> drying (the current standard) with alternative ambient drying routes. Both energy use and CO<sub>2</sub> emissions are substantial for both methods, underscoring the importance of process improvements and precursor selection in lowering the environmental footprint of silica aerogel production.