CO_2 Power Pathways: Which Is Most Efficient, and What a Combined "Supermotive" Engine Would Look Like

Turbine-generator vs turbine-hydraulic vs heated-piston hydraulic vs CO_2-entrained ferrofluid · Infinity Turbine LLC · November 2026

1. Summary

The CO_2 thermodynamic cycle sets the ceiling, and each extra conversion step after the expander removes a few percent. **For electricity, a CO_2 turbine directly driving a high-speed generator is the most efficient route** wherever the scale supports a good turbine (roughly 100 kW and up, and especially multi-MW sCO_2 Brayton at 500–700 °C, where cycle efficiencies reach 40–50%). **When the output you need is hydraulic force, especially at small scale (10–200 kW) and low speed, a CO_2 piston expander driving hydraulic fluid directly is the most efficient route.** It skips the generator and pump stages and suits the high pressure ratios and low flow rates where small turbines perform poorly.

Spinning a turbine to make hydraulic pressure only makes sense when hydraulic output is the end use. CO_2-entrained ferrofluid is the least efficient by a wide margin, below 1% heat-to-work. Its magnetic forces are about 1,000× weaker than hydraulic pressure, and CO_2 attacks the fluid's chemistry.

The best combined design is a **double-acting free-piston CO_2 expander**. Its rod carries a permanent-magnet section inside copper coils, which form a linear alternator and motor, and ends in a hydraulic plunger. Ferrofluid serves as rod seals and gap coolant, and MR fluid as the stroke damper. It does not beat thermodynamics. Its advantage is that it eliminates the crankshaft, gearbox, rotary generator and separate pump, and delivers electricity, hydraulic power or both from one moving part.

2. The four CO_2 pathways

Path	Description	Conversion chain
A **Turbine → generator**	CO_2 expands through a radial, axial or Tesla turbine on the same shaft as a high-speed PM generator. Power electronics condition the output.	Heat → CO_2 → turbine shaft → generator → electricity
B **Turbine → hydraulic**	The turbine drives a hydraulic pump, through a gearbox if speeds don't match. Oil pressure drives cylinders or a hydraulic motor.	Heat → CO_2 → turbine → (gearbox) → pump → oil → motor or cylinder

Path	Description	Conversion chain
C **Heated CO_2 piston → hydraulic cylinder**	High-pressure CO_2 from an external heater is admitted to a piston expander. The piston acts directly on a hydraulic plunger, with no crank. A batch variant heats CO_2 inside the cylinder itself.	Heat → CO_2 → piston → oil (direct) → cylinder or motor
D **CO_2 entrained in ferrofluid**	CO_2 dissolved or bubbled in a ferrofluid is heated to release and expand it, pressurizing the liquid. Optionally a magnetic field pumps it (thermomagnetic effect), or the moving fluid passes through coils.	Heat → CO_2 desorption/expansion and ferrofluid magnetization → liquid pressure → (coil EMF)

3. Efficiency analysis

3.1 Downstream conversion chain (what survives after the CO_2 expands)

Each figure below multiplies typical component efficiencies. It shows how much of the ideal CO_2 expansion work reaches the useful output.

A turbine 0.60–0.88 × generator 0.95–0.97 × power electronics 0.96–0.98 = **0.55–0.84 electric**

B turbine 0.60–0.88 × gearbox 0.97 × pump 0.90–0.93 × lines/valves 0.90–0.95 × cylinder 0.95 = **0.45–0.70 hydraulic** (→ electric via hyd. motor + generator: 0.38–0.60)

C piston expander 0.65–0.82 × direct oil transfer 0.90–0.95 = **0.59–0.78 hydraulic** (→ electric via hyd. motor + generator: 0.50–0.66)

D desorption/thermomagnetic conversion ≪ 0.05 = **<0.05** (coil EMF from ferrofluid adds further loss)

S free-piston expander 0.70–0.84 × linear alternator 0.90–0.94 × electronics 0.97 = **0.61–0.77 electric**, or 0.63–0.80 hydraulic via the plunger

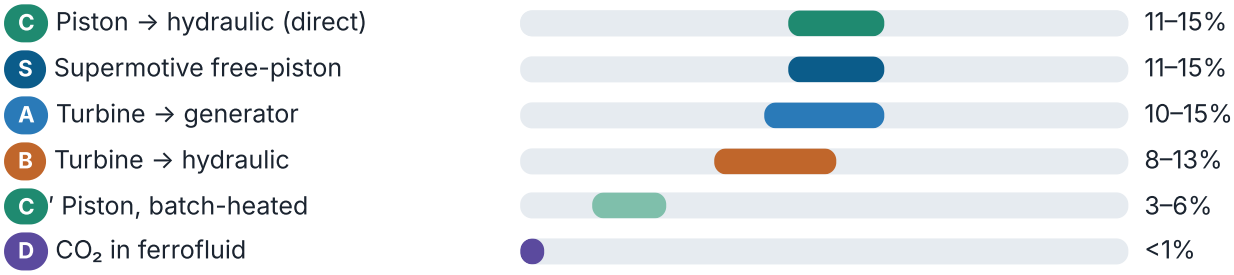
3.2 Heat-to-output, indicative ranges

Path	Large scale (>5 MW, 550–700 °C, sCO_2 Brayton)	Small scale (50–150 kW, ~250 °C, transcritical Rankine)	Low grade (≤110 °C, transcritical Rankine)	Output type
A **Turbine → generator**	**40–50%**	10–15%	5–8%	Electricity
B **Turbine → hydraulic**	32–42% (rarely used)	8–13%	4–6%	Hydraulic
C **Piston → hydraulic (external heater, recuperated)**	Not practical (flow too large)	**11–15%**	5–8%	Hydraulic

Path	Large scale (>5 MW, 550–700 °C, sCO_2 Brayton)	Small scale (50–150 kW, ~250 °C, transcritical Rankine)	Low grade (≤110 °C, transcritical Rankine)	Output type
C′ **Piston, batch-heated in cylinder**	—	3–6%	1–3%	Hydraulic
D **CO_2-entrained ferrofluid**	—	<1%	<0.5%	Liquid pressure, µW–W electric
S **Supermotive free-piston**	Not practical	**11–15%** (electric or hydraulic)	5–8%	Both

Ranges are net of CO_2 pump work and use realistic heat-exchanger approach temperatures and recuperation. Carnot limits for reference: about 65% at 650 °C, about 45% at 250 °C, about 26% at 110 °C (sink at 10–15 °C). Use these for screening only. Design numbers need a cycle model with real fluid properties (e.g., REFPROP/CoolProp).

3.3 Visual ranking: small scale (~250 °C, 50–150 kW)



Scale: 0–25% heat-to-output.

3.4 Verdict

1 **Large scale, electricity:** A sCO_2 turbine with a direct high-speed generator. No other path comes close at MW scale and high temperature.

1 **Small scale, hydraulic output:** C piston expander driving oil directly. It needs an external heater, a recuperator, timed inlet valves and a crankless free piston. This is the best match for a remote wood-fired system whose job is hydraulic work.

2 **Small scale, electricity:** A and S are close. Low-cost turbines (e.g., 1,800–3,600 rpm direct-drive) are simpler. A free-piston linear alternator wins where pressure ratios are high and flows small.

3 B is worthwhile only when hydraulic output is the end goal and a turbine already exists.

4 D is a research curiosity, not a power path (see Section 4).

> **Why piston expanders win at small scale:** Transcritical CO_2 runs at roughly 60–140 bar with pressure ratios of 2–3 and very small volumetric flow because the fluid is dense. A small turbine then needs tiny blades at very high rpm, where tip leakage and friction dominate. A positive-displacement piston handles high pressure and low flow well at low speed, and couples naturally to hydraulic fluid, which is also a high-pressure, low-flow medium.

> **Batch heating is a trap:** Heating CO_2 inside the working cylinder and then cooling it again means cycling the cylinder's metal mass every stroke. This makes it slow, adds large heat losses and leaves no room for a recuperator, which costs 50–70% of the possible output. Heat CO_2 in a separate heat exchanger, admit it through valves and recuperate the exhaust.

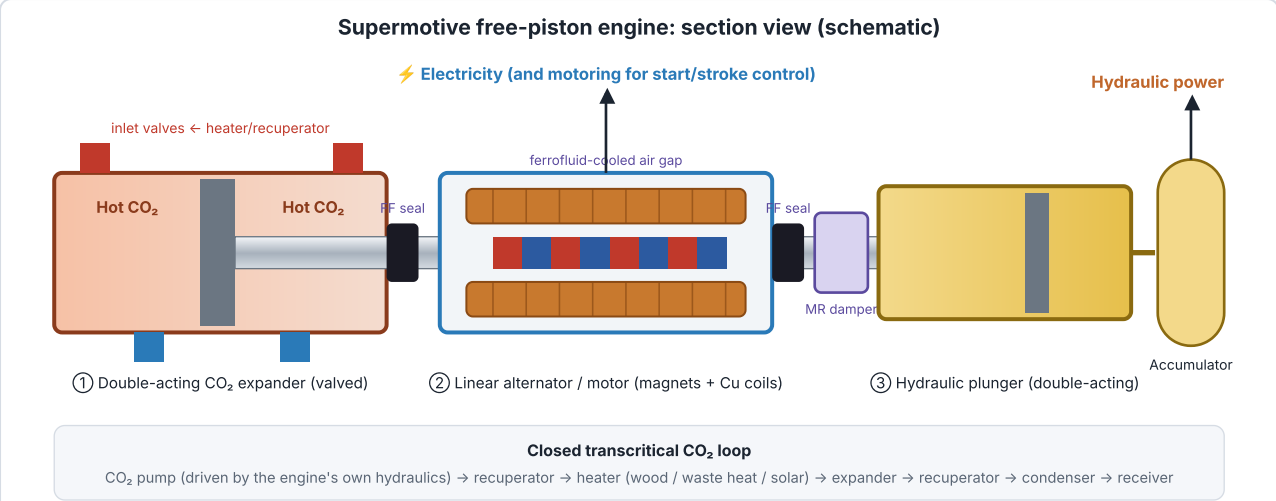
4. CO_2-entrained ferrofluid: a hard look

Issue	Detail	Consequence
Weak magnetic force	Ferrofluid saturation magnetization is about 30–90 kA/m, giving magnetic pressure of about 1–10 kPa. Hydraulic oil runs at 20–40 MPa and CO_2 at 6–14 MPa.	The magnetic contribution is about 1/1,000 to 1/10,000 of the CO_2 or hydraulic pressure, so it adds essentially nothing to power.
Coils around flowing ferrofluid	Flux from a ferrofluid slug is about $\mu_0 M \approx 0.04–0.1$ T, vs 1.2–1.4 T for NdFeB. Induced power scales roughly with B^2.	About 150–1,000× less power per unit volume than a magnet-piston linear alternator. Entrained gas bubbles dilute it further.
CO_2 chemistry	Pressurized and supercritical CO_2 dissolves in or extracts hydrocarbon and ester carrier oils and is highly soluble in fluorocarbons. In water carriers it forms carbonic acid, which attacks magnetite.	Swelling, foaming on depressurization, surfactant stripping, particle clumping and loss of the colloid.
Thermomagnetic pumping	Works by magnetization falling as temperature approaches the particle Curie point (magnetite is about 585 °C, so only a small change across practical ΔT).	Heat-to-work efficiency well under 1%. Useful only for no-moving-part circulation at very low head.
Gas-in-liquid expansion	Releasing dissolved CO_2 by heating does pressurize a liquid, but it is an unrecuperated batch process.	Behaves like batch heating (C′) with even worse heat transfer and slower dynamics.

> **Where ferrofluid does earn a place:** as magnetic liquid seals on the moving rod at low-pressure boundaries, as a coolant in the alternator air gap, and as a small no-moving-part circulator for cooling loops. Its relative MR fluid is useful as an electronically controlled end-of-stroke damper and brake. Use solid permanent magnets for the electricity-making part.

5. The Supermotive Free-Piston CO_2 Engine (combined concept)

This concept puts all three motion types on one moving rod: **linear CO_2 expansion**, **electromagnetic conversion** (coils around a magnet section, the rotary motor's principle unrolled into a line) and **hydraulic force**. Magnetic fluids act as enablers.



5.1 Components and what each does

Element	Function	Motion type	Design notes
① **Double-acting CO_2 expander**	Hot, high-pressure CO_2 is admitted alternately to each side of the piston through timed valves, expands, then exhausts to the recuperator.	Linear (thermal)	Electronically timed solenoid or rotary valves set the cutoff, the expansion ratio being matched to load. Piston rings or clearance seal plus a buffer zone. Hot end isolated thermally from the magnets.
② **Linear alternator / motor**	A NdFeB or SmCo magnet section on the rod moves inside copper coils to generate electricity. The same coils act as a linear motor to start, centre and control the stroke, replacing the crank and flywheel.	Electromagnetic	Keep magnets below their temperature limit (NdFeB about 80–150 °C; SmCo to about 300 °C). Proven in free-piston Stirling engines, where alternators reach 90%+ efficiency. An active rectifier/inverter controls stroke frequency and amplitude.
③ **Hydraulic plunger**	The rod end pumps oil into an accumulator. Valves set the split between electrical and hydraulic output, or switch to hydraulic only.	Hydraulic (linear)	Area ratio between CO_2 piston and plunger sets pressure intensification (e.g., 100 bar CO_2 → 250–300 bar oil). The accumulator smooths pulses. Can drive the CO_2 feed pump directly.
Ferrofluid seals	Zero-leak, low-friction magnetic liquid seals on the rod between sections.	Magnetic fluid	Only at low-pressure boundaries (about 0.2–0.3 bar per stage). The main CO_2 pressure is held by rings or labyrinths, with ferrofluid as the final buffer. Choose a carrier fluid for CO_2 compatibility and test it.

Element	Function	Motion type	Design notes
Ferrofluid gap coolant	Fills the alternator air gap to carry coil heat to the housing and slightly increase flux.	Magnetic fluid	Static fluid with no CO_2 contact. Proven in loudspeakers.
MR fluid damper	Electronically controlled end-of-stroke cushion and emergency brake if load is lost.	Semi-magnetic fluid	Responds in 5–20 ms. Prevents piston over-travel, which is the main failure mode of free-piston machines.

5.2 Why this combination makes sense

- **Fewer conversions:** no crankshaft, connecting rods, gearbox, rotary generator or separate hydraulic pump. One moving assembly does all three jobs.
- **Dual output:** electricity and hydraulic power from the same stroke, dispatched by valve logic. This suits remote sites such as mining, where both are needed.
- **Variable expansion:** electronic valve timing plus coil force control gives good part-load efficiency, which turbines lack.
- **Self-contained loop:** plunger hydraulics can drive the CO_2 feed pump, so the system is self-sustaining once started by the coils in motor mode.
- **Few side-loads:** a free piston has almost no lateral force, so seal wear is low and ferrofluid seals have an easier job.

5.3 Main engineering risks

Risk	Mitigation
Stroke control (no crank sets the stroke limits)	Closed-loop coil force control, position sensing, MR end dampers and a hydraulic end cushion.
Magnet temperature	Tandem layout with the hot cylinder separated from the alternator, a cooled rod section, SmCo magnets, and ferrofluid gap cooling.
CO_2 blow-by and sealing at 60–140 bar	Stepped seals: rings, then labyrinth, then a vented buffer, then a ferrofluid final seal. Return blow-by to the condenser side.
Valve losses and timing	Large-area fast valves, cam-less electronic actuation, and inlet cutoff tuned to the expansion ratio.
Vibration from a single piston	Opposed twin pistons on one axis (mirror-image units) to balance the forces.
Power density vs turbines	Accept a larger size for lower cost and robustness at 10–200 kW. Scale up with modular clusters rather than larger units.

6. Worked example: 500,000 BTU/hr wood-fired heater (~146 kW thermal)

Path	Heat-to-output	Net output	Comment
A Turbine → generator	10–15%	15–22 kWe	Turbine efficiency at this size is the limiting factor.
B Turbine → hydraulic	8–13%	12–19 kW hydraulic	Extra pump stage. Gearbox if turbine speed is high.
C Piston → hydraulic (direct)	11–15%	16–22 kW hydraulic	Best for hydraulic-only duty.
C′ Batch-heated piston	3–6%	4–9 kW hydraulic	Avoid.
D CO_2 in ferrofluid	<1%	<1.5 kW	Not viable.
S Supermotive free-piston	11–15%	16–22 kW (any mix of electric and hydraulic)	Same efficiency as C, plus electricity and self-starting.

Assumes CO_2 heated to about 220–260 °C by the flue-gas/thermal-oil loop, cooling water at about 10–15 °C, recuperation, and net of CO_2 pump work. Wood boiler efficiency (typically 65–80%) is *not* included. Multiply by it for fuel-to-output figures.

7. Recommended development path

1. **Prove C first:** an externally heated, recuperated CO_2 piston expander driving a hydraulic plunger and accumulator. Measure indicated work, blow-by and valve losses.
2. **Add the linear alternator** on a cool section of the same rod, and use it for motor-start and stroke control.
3. **Add ferrofluid buffer seals and gap cooling** after the main CO_2 seal stack is proven. Run carrier-fluid compatibility soak tests in CO_2 at operating pressure first.
4. **Add MR end-of-stroke dampers** and closed-loop control. Then build an opposed twin for balance.
5. **Benchmark against a turbine-generator** on the same CO_2 loop at the same heat input and sink temperature.
6. **Treat CO_2-entrained ferrofluid as bench research only**, e.g., a no-moving-part coolant circulator.

Efficiency figures are indicative engineering ranges for concept screening, built from typical component efficiencies and published CO_2 cycle performance. Confirm with a detailed cycle model and test data before design commitments.

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