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Transcritical CO_2 Waste-Heat-to-Hydraulic Power System with Positive-Displacement Cylinder Expanders

Thermodynamic analysis, P&ID, state points, flows, pressures and power output for a CO_2 cycle heated by 100 °C (212 °F) hot water and cooled by 15 °C (59 °F) water. The CO_2 drives pistons that pump hydraulic oil directly. The heat source is a 500,000 BTU/h wood-fired burner.

12.2 kW
Gross hydraulic power · 16.4 hp (Option B)

5.3 kW
Net hydraulic after CO_2 feed pump · 7.2 hp

35.5 L/min
Oil flow at 207 bar · 9.4 gpm at 3,000 psi

5.4 %
Cycle efficiency on 117 kW (400,000 BTU/h) heat

01 Summary

What the system is, what it can produce, and the main design decisions.

Concept. CO_2 is pumped as a liquid to about **110 bar (1,595 psia)**, above its critical pressure of 73.8 bar. It is heated by 100 °C water to 95 °C (203 °F) and admitted to double-acting cylinders. Each CO_2 piston is joined by a rod to a hydraulic plunger. The plunger draws oil from the reservoir and pushes it through check valves into an accumulator at **207 bar (3,000 psi)**. The exhaust CO_2 (about 58 bar, 48 °C) gives up heat in a recuperator. It is then condensed at **20 °C / 57 bar (68 °F / 831 psia)** with 15 °C cooling water and pumped back to high pressure.

Why CO_2. With a 15 °C sink, CO_2 condenses below its 31 °C critical temperature. That allows a real liquid pump and a transcritical cycle. The working pressures are high, so the gas is dense and a short-stroke piston expander stays compact. The pressures also fall naturally in the range of industrial hydraulic components.

Power. The 500,000 BTU/h burner delivers about **117 kW (400,000 BTU/h)** to the hot-water loop at 80 % boiler efficiency. That heat gives **11.2–12.2 kW (15–16 hp) of gross hydraulic power**. After the CO_2 feed pump is driven, **4.3–5.3 kW (5.7–7.2 hp) of net hydraulic power** is left over.

Headline results (design point, 110 bar)

	Option A full admission	Option B cutoff + expansion
Heat to CO_2	117.2 kW 400,000 BTU/h	117.2 kW 400,000 BTU/h
CO_2 mass flow	0.596 kg/s 4,730 lb/h	0.591 kg/s 4,690 lb/h
Expander indicated work	12.2 kW · 16.4 hp	13.3 kW · 17.8 hp

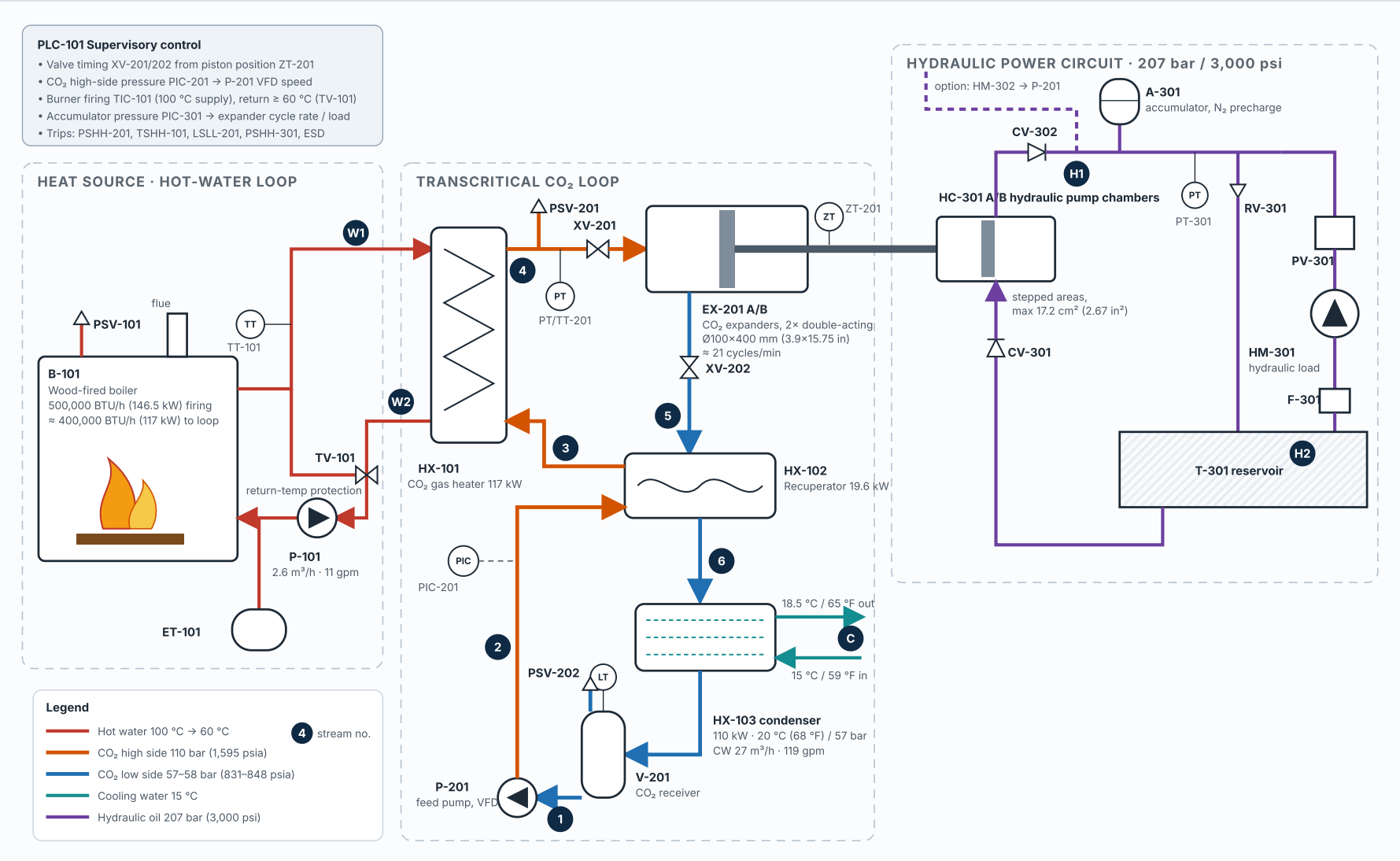
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Gross hydraulic out	11.2 kW · 15.1 hp	12.2 kW · 16.4 hp
CO_2 feed pump (shaft)	5.9 kW · 7.9 hp	5.9 kW · 7.9 hp
Net hydraulic, self-powered*	**4.3 kW · 5.7 hp**	**5.3 kW · 7.2 hp**
Oil flow at 207 bar / 3,000 psi	32.6 L/min · 8.6 gpm	35.5 L/min · 9.4 gpm
Cycle efficiency	4.5 %	5.4 %
Fuel → net hydraulic	2.9 %	3.6 %

*CO_2 feed pump driven by a hydraulic motor (85 % efficient) from the system's own output. If the pump is driven by an electric motor instead, the full gross hydraulic power is available and the pump draws about 6.5 kW of electricity.

02 Piping & instrumentation diagram

Three circuits: pressurised hot water, transcritical CO_2, and 207 bar hydraulic oil. Stream numbers refer to the state table in Section 03.



P&ID — transcritical CO_2 cylinder-expander system, heated by hot water and producing hydraulic power. Tags follow ISA-5.1 style: B boiler, HX heat exchanger, P pump, XV on/off valve, TV temperature valve, PSV pressure-safety valve, CV check valve, RV relief valve, A accumulator, T tank, PT/TT/LT/ZT pressure, temperature, level and position transmitters, PIC pressure-indicating controller.

Equipment list

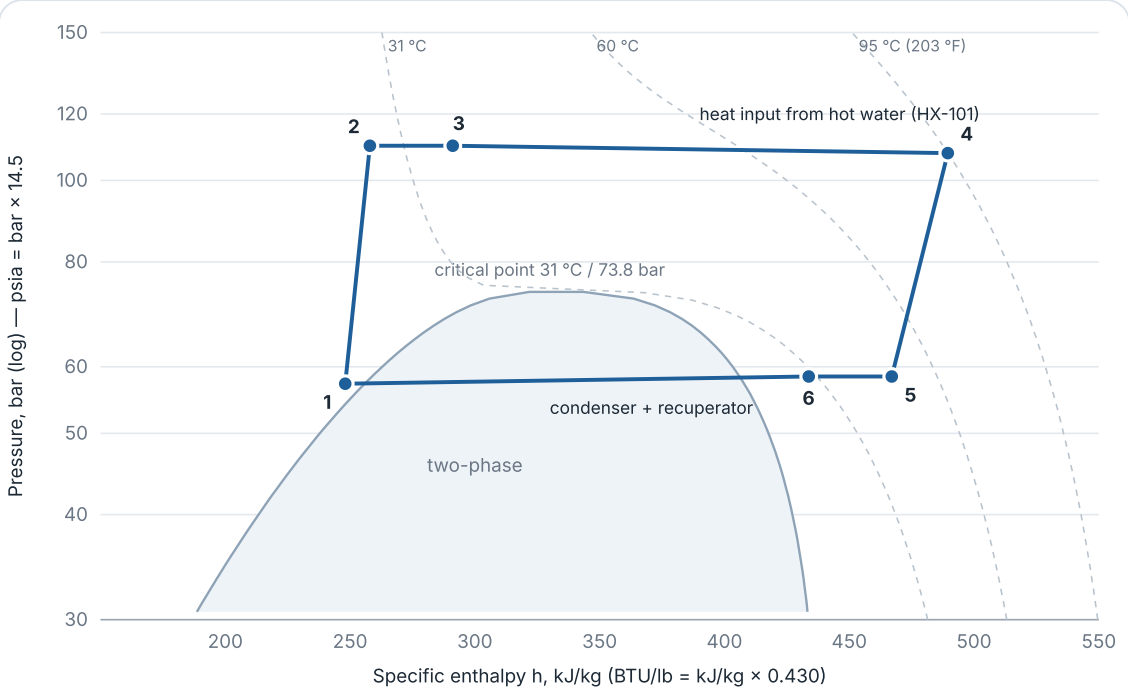
Tag	Service	Duty / size	Design conditions
B-101	Wood-fired hot-water boiler	500,000 BTU/h (146.5 kW) firing; ~400,000 BTU/h (117 kW) to the loop	110 °C / 230 °F; 6 bar(g) / 87 psig
P-101	Hot-water circulation pump	2.6 m³/h (11.4 gpm), ~1.5 bar (22 psi) head; ~0.25 kW	110 °C; 6 bar(g)
TV-101	3-way return-temperature valve	Keeps boiler return ≥ 60 °C (140 °F) against creosote and condensation	—
ET-101	Expansion tank	Loop pressurised to ~3 bar(g) (44 psig) so 100 °C water stays liquid	6 bar(g)
HX-101	CO_2 gas heater (water → CO_2), counterflow	117 kW (400,000 BTU/h); 5 K (9 °F) hot-end approach	CO_2 side 130 bar / 1,885 psig, 120 °C
EX-201 A/B	CO_2 expander cylinders, double-acting	Ø100 mm × 400 mm stroke (3.94 × 15.75 in), 2 off	130 bar, 120 °C
XV-201/202	Admission / exhaust valves (4 per cylinder)	Hydraulically actuated poppets timed from ZT-201	130 bar, 120 °C
HX-102	Recuperator (LP vapour → HP liquid)	19.6 kW (66,900 BTU/h), effectiveness 0.80	130 bar both sides
HX-103	Condenser (CO_2 → cooling water)	110 kW (374,700 BTU/h), condensing at 20 °C (68 °F)	CO_2 90 bar / 1,305 psig
V-201	CO_2 liquid receiver	Holds the charge inventory; gives the pump suction head	90 bar (PSV-202 set point)
P-201	CO_2 feed pump, VFD (plunger or diaphragm type)	44 L/min (11.7 gpm), 57 → 110 bar (831 → 1,595 psia); 5.9 kW shaft	130 bar
HC-301 A/B	Hydraulic pump chambers in tandem with EX-201	Max area 17.2 cm² (2.67 in²); stepped areas for Option B	250 bar / 3,625 psi
A-301	Bladder accumulator	Evens out the pulsing flow; ~20–40 L (5–10 gal)	250 bar
RV-301 / PV-301	Relief valve / proportional load valve	Relief set at 230 bar (3,340 psi)	—
HM-301	Hydraulic consumer (motor, press, lift, etc.)	Up to ~12 kW at 207 bar (~5.3 kW if HM-302 also drives P-201)	—
T-301 / F-301	Reservoir / return filter	~100 L (26 gal), 10 µm return filter	Atmospheric

03 Cycle state points (Option B, 110 bar)

Properties from CoolProp (Span–Wagner equation of state for CO_2). Mass flow 0.591 kg/s (4,690 lb/h). Enthalpy reference: IIR (h = 200 kJ/kg for saturated liquid at 0 °C).

#	Location	Pressure bar / psia	Temperature °C / °F	Enthalpy kJ/kg / BTU/lb	Density kg/m³ / lb/ft³	Phase
1	Pump suction (receiver outlet)	57.3 / 831	18.0 / 64.4	248.0 / 106.6	801 / 50.02	subcooled liquid
2	Pump discharge	110.0 / 1,595	26.4 / 79.5	257.9 / 110.9	822 / 51.31	compressed liquid

3	Recuperator cold-side outlet	110.0 / 1,595	37.1 / 98.7	291.2 / 125.2	721 / 45.00	supercritical (liquid-like)
4	Gas-heater outlet / cylinder admission	107.8 / 1,564	95.0 / 203.0	489.5 / 210.5	217 / 13.53	supercritical
5	Cylinder exhaust	58.4 / 848	47.7 / 117.8	467.0 / 200.8	133 / 8.29	superheated vapour
6	Recuperator hot-side outlet	58.4 / 848	29.7 / 85.5	433.8 / 186.5	163 / 10.20	superheated vapour



CO_2 pressure–enthalpy diagram with the design cycle: 1→2 pump, 2→3 recuperator (cold side), 3→4 gas heater, 4→5 cylinder expansion, 5→6 recuperator (hot side), 6→1 desuperheat, condense and subcool.

Heat and fluid flows

Stream	Metric	Imperial
Fuel firing (wood)	146.5 kW	500,000 BTU/h
Heat to loop (80 % boiler)	117.2 kW	400,000 BTU/h
Hot water W1→W2	100→60 °C, 0.70 kg/s, 2.6 m³/h	212→140 °F, 11.4 gpm
CO_2 mass flow	0.591 kg/s · 2,128 kg/h	4,690 lb/h
CO_2 liquid to pump (1)	44.3 L/min	11.7 gpm
CO_2 at cylinder inlet (4)	2.73 L/s · 164 L/min	5.8 ft³/min
CO_2 at cylinder exhaust (5)	4.45 L/s · 267 L/min	9.4 ft³/min
Recuperator duty	19.6 kW	66,900 BTU/h
Condenser duty	109.8 kW	374,700 BTU/h
Cooling water C	15→18.5 °C, 7.5 kg/s, 27 m³/h	59→65 °F, 119 gpm
Hydraulic oil H1	35.5 L/min at 207 bar	9.4 gpm at 3,000 psi

Energy balance: 117.2 kW heat + 5.9 kW pump work = 13.3 kW expander work + 109.8 kW rejected (closes within 0.1 kW). The cooling water heats up only 3.5 K because the condenser runs with a 2 K pinch to hold CO_2

condensing at 20 °C. Accepting a 22–23 °C condensing temperature would halve the cooling-water flow, at a cost of about 0.4–0.5 percentage points of efficiency.

04 Expander: CO_2 cylinders driving hydraulic oil

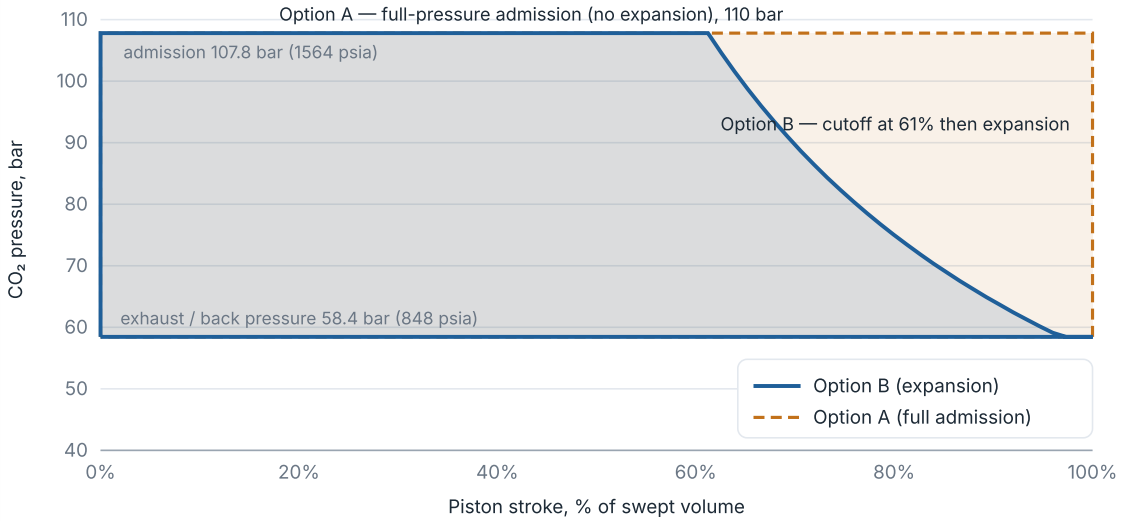
How the piston expander is coupled to the hydraulic circuit, and why two options are analysed.

A free-piston CO_2 cylinder is joined directly to a hydraulic plunger, so **the force on the CO_2 piston and the oil pressure are tied by a fixed area ratio**. The hydraulic side wants a constant pressure (207 bar), so the CO_2 force should also be constant across the stroke. That leads to two ways of running the cylinder:

Option A: full-pressure admission. The inlet valve stays open for the whole stroke, so CO_2 at 107.8 bar pushes against 58.4 bar back pressure. The 49.4 bar (717 psi) net pressure acts on a 78.5 cm² piston, giving a **constant force of 38.8 kN (8,720 lbf)**. That matches a 17.2 cm² (Ø46.8 mm / 1.84 in) plunger at 207 bar, after 8 % seal and friction loss. It is simple, self-regulating and robust. The penalty is that the cylinder is exhausted while still at full pressure, which loses about 9 % of the available work. A modelled 0.90 factor covers valve throttling and leakage.

Option B: cutoff and expansion. The inlet valve closes at about **61 % of the stroke** and the CO_2 expands for the rest (volume ratio 1.63). Force falls from 38.8 kN to almost zero by the end of the stroke. The hydraulic side follows it with **stepped (digital) plunger areas**, such as three chambers switched by valves, or a crank and flywheel driving a rotary pump. Assuming 80 % indicated efficiency, it gives **+9 % hydraulic power and +25 % net power**, at the cost of more valves and controls.

> Recommendation: build **Option A first** to prove the valve gear, seals, CO_2 pump and control. Add the stepped hydraulic areas of Option B as a later upgrade on the same cylinders.



Indicator (pressure–stroke) diagram for one CO_2 cylinder stroke. The enclosed area is the work per unit of swept volume. Option B gets more work out of each kilogram of CO_2, but needs a larger swept volume and a force on the hydraulic side that changes over the stroke.

Cylinder sizing

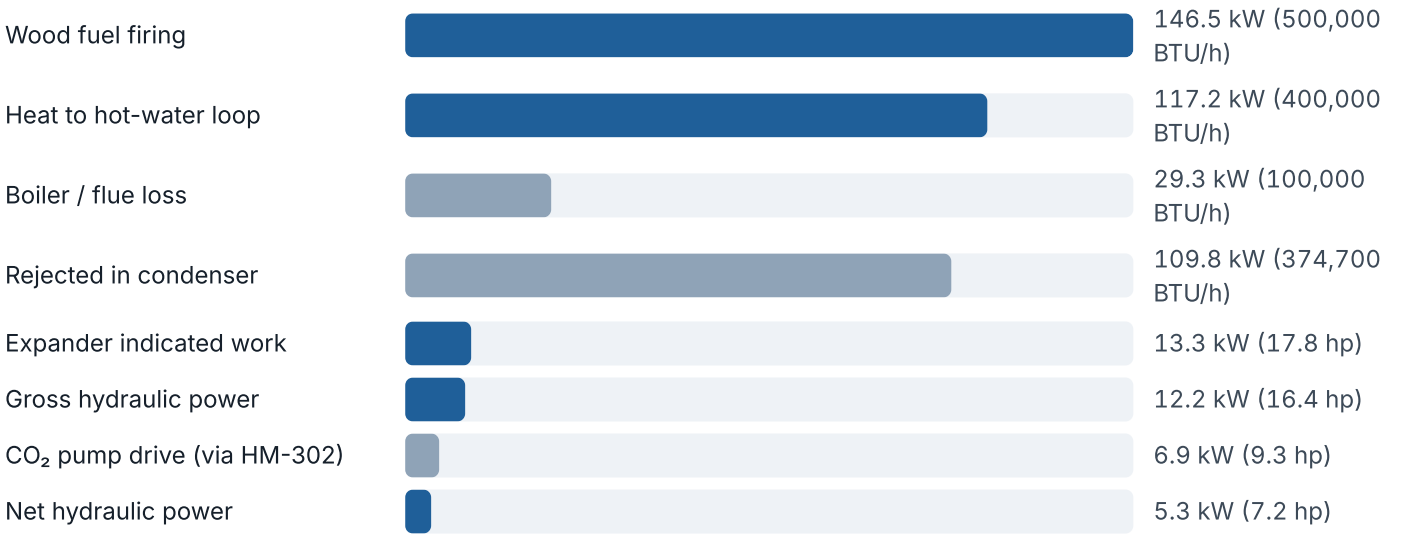
Item	Option A	Option B

Cylinders	2 × double-acting	2 × double-acting
CO_2 bore × stroke		Ø100 × 400 mm · Ø3.94 × 15.75 in
Swept CO_2 volume flow	2.75 L/s · 5.8 cfm	4.45 L/s · 9.4 cfm
Cycle rate	13 cycles/min	21 cycles/min
Mean piston speed	0.17 m/s · 34 ft/min	0.28 m/s · 56 ft/min
Peak rod force	38.8 kN · 8,720 lbf	38.8 kN · 8,720 lbf
Mean rod force	38.8 kN · 8,720 lbf	23.5 kN · 5,280 lbf
Hydraulic plunger area	17.2 cm² · 2.67 in²	stepped, 17.2 → ~5 cm²
Oil delivered at 207 bar	32.6 L/min · 8.6 gpm	35.5 L/min · 9.4 gpm

The low piston speeds keep valve losses and seal wear down. Cycle rate can be raised to shrink the cylinders, but each doubling adds valve-throttling loss.

05 Power from a 500,000 BTU/h wood-fired burner

Where the heat goes, Option B, self-powered configuration.



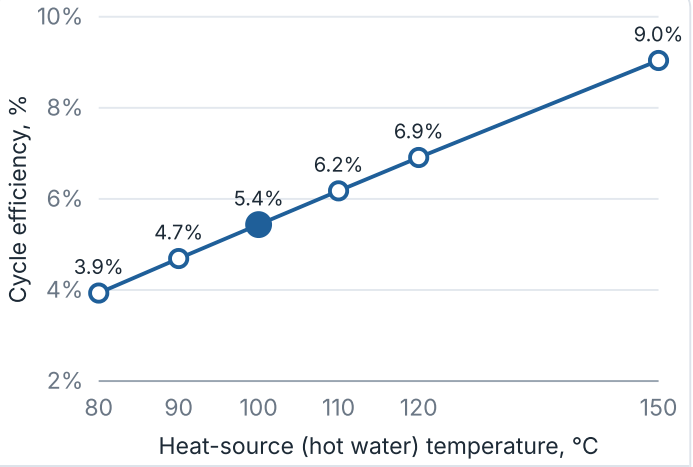
Bar length is proportional to power. Values in kW, with hp or BTU/h in brackets. Plant parasitic loads (about 0.25 kW hot-water pump, 1.0 kW cooling-water pump or fan, 0.3–0.5 kW boiler draft fan and controls) come on top. They total roughly 1.5–2 kW of electricity unless the cooling water flows by gravity or from a well.

Why the efficiency is only about 5 %

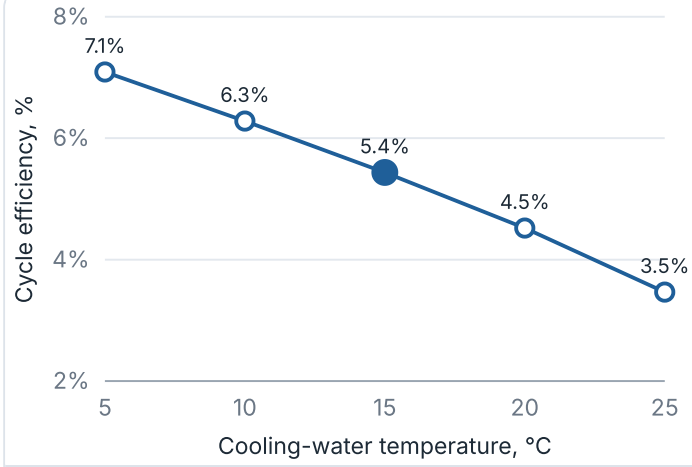
The hot water drops from 100 to 60 °C, so heat arrives at an average of about 80 °C (353 K) and leaves at about 15 °C (288 K). The Carnot limit for that is about 18 %. The cycle reaches about 30 % of Carnot. That is normal for a small transcritical CO_2 cycle with a 100 °C source. Two features of CO_2 dominate:

- **High pump work.** Pumping CO_2 from 57 to 110 bar takes 48 % of the gross expander output. Feed-pump efficiency is the most important single assumption: raising it from 65 % to 80 % lifts net power from 5.3 to 6.6 kW (7.2 → 8.9 hp).
- **Small pressure ratio.** The cylinders work across only 1.85:1, so leakage, valve pressure drop and heat transfer in the cylinder matter. Tight, well-insulated cylinders and low-loss poppet valves are essential.

Sensitivity



Hot-water supply temperature (CO_2 5 K below it, high pressure re-optimised). Design point filled.



Cooling-water temperature (condensing 5 K above it).

Case (117 kW heat, Option B)	Cycle η	Net hydraulic*
Design: 100 °C source / 15 °C water	5.4 %	5.3 kW · 7.2 hp
120 °C source (248 °F)	6.9 %	≈ 7.1 kW · 9.5 hp
150 °C source (302 °F, pressurised water)	9.0 %	≈ 9.5 kW · 12.7 hp
Winter cooling water 5 °C (41 °F)	7.1 %	≈ 7.3 kW · 9.8 hp
Summer cooling water 25 °C (77 °F)	3.5 %	≈ 3.0 kW · 4.0 hp
If 500,000 BTU/h is the boiler *output* (146.5 kW)	5.4 %	6.7 kW · 9.0 hp

*Off-design net values are estimated by scaling the design-point split between gross power and pump power. Treat them as ±10 %.

Design note for the wood burner. A wood fire burns at more than 1,000 °C. Limiting the system to 100 °C water is the right choice when the target application is genuine waste heat, such as engine jacket water, process cooling or flue-gas economisers, and the wood burner is only a test or backup heat source. If the wood burner will be the main heat source, a **pressurised hot-water or thermal-oil loop at 150 °C** would nearly double the hydraulic output from the same wood. CO_2 high pressure would rise to about 145 bar.

06 Control philosophy and safety

Control loops

- **TIC-101:** burner firing rate (draft fan or air damper) holds hot-water supply at 100 °C. A **hot-water buffer tank** (≥ 1,000 L / 260 gal) is recommended because a wood fire responds slowly.
- **TV-101:** 3-way valve holds boiler return ≥ 60 °C.
- **PIC-201:** the P-201 VFD sets CO_2 flow to hold the high side at 110 bar. The heater outlet temperature then follows the heat available.

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- **ZT-201 → PLC:** piston position drives XV-201/202 timing (admission, cutoff, exhaust) and reverses the double-acting stroke. Option B also switches the hydraulic area steps.
- **PIC-301:** accumulator pressure. The PLC lowers the expander cycle rate or opens PV-301 to hand power to the load. RV-301 is the final protection.
- **Start-up:** circulate hot water, run P-201 on recirculation until stream 4 exceeds 80 °C, then enable the valve sequence. Use battery or hydraulic hand-pump assist for the first strokes.

Safety and code items

- CO_2 high side up to 130 bar (1,885 psig) design: PSV-201 on the heater/expander side, PSV-202 on receiver and low side (90 bar). Every isolatable liquid-CO_2 section needs thermal relief, because trapped liquid CO_2 expands sharply when it warms.
- In the EU this is a pressure system under the Pressure Equipment Directive 2014/68/EU; in the US, ASME BPVC Section VIII and B31.3 (B31.5 refrigeration practice). Hydraulic side per ISO 4413.
- CO_2 is an asphyxiant. Indoor installations need a CO_2 gas detector (alarm at 5,000 ppm), ventilation, and relief valves vented outdoors.
- Standstill: on a warm day the stopped system's pressure rises toward the CO_2 saturation pressure at ambient (about 64 bar at 25 °C; supercritical above 31 °C). Size the low side for this, or fit a small standstill condensing unit.
- Trips: PSHH-201 (high CO_2 pressure), TSHH-101 (boiler overheat, wood fire dump zone), LSLL-201 (receiver low level, pump dry-run), PSHH-301 (hydraulic overpressure), emergency stop.
- Wood boiler: overheat heat-dump loop (gravity-fed to a dump radiator) per the boiler manufacturer and EN 303-5 / UL 391.

07 Conclusions

About 12 kW (16 hp) of hydraulic power, about 5 kW (7 hp) net, from 500,000 BTU/h of wood at 100 °C

- A transcritical CO_2 cycle between 100 °C water and 15 °C water works with a **110 bar high side and a 57 bar condensing pressure**. Every component is within ordinary high-pressure hydraulic and CO_2-refrigeration practice.
- Coupling CO_2 pistons directly to hydraulic plungers avoids a crankshaft, a generator and a hydraulic pump. At about 21 cycles/min, two Ø100 × 400 mm cylinders deliver **35 L/min (9.4 gpm) of oil at 207 bar (3,000 psi)**.
- The main losses are the CO_2 feed pump (48 % back-work ratio) and the low source temperature. Pump efficiency, valve losses and leakage decide whether the net figure is 4 or 7 kW.
- For a **true waste-heat application at 100 °C**, the system is a credible, simple way to get hydraulic power without an electrical conversion step. When wood is the main fuel, raising the loop to **150 °C** is the most effective upgrade (≈ +80 % net power).

Basis and assumptions

Parameter	Value used
Boiler (wood → hot water) efficiency	80 % (500,000 BTU/h taken as fuel firing rate)
Hot-water supply / return	100 °C / 60 °C (212 / 140 °F); heater hot-end approach 5 K (9 °F)
Cooling water / condensing	15 °C in (59 °F); condensing 20 °C (68 °F), 57.3 bar; liquid subcooled to 18 °C
Expander indicated efficiency	Option B 80 % isentropic; Option A 90 % of ideal full-admission work
CO_2 piston → hydraulic transfer	92 % (seals, rod friction, check valves)
CO_2 feed pump	65 % isentropic; motor 90 % (electric) or hydraulic motor 85 %
Recuperator effectiveness / pressure drops	0.80; 2 % pressure loss in each of heater and low-side path
Hydraulic system pressure	207 bar (3,000 psi)
Property data	CoolProp 8 (Span–Wagner CO_2, IAPWS water)

This is a preliminary feasibility analysis, not a certified design. Vessel, piping and relief sizing must be confirmed by detailed design to the applicable codes.

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