ENGINEERING COMPARISON · INFINITY TURBINE LLC · YUKON PLACER GOLD APPLICATION · NOVEMBER 2026

# Steam Engine vs Steam Turbine vs $CO_2$ Bucket Turbine vs $CO_2$ Piston Expander for Wood-Fired Hydraulic Power

Same 500,000 BTU/h log boiler, same 800 °C flue gas, same 5 °C (41 °F) creek/glycol cooling, and the same deliverable in every case: hydraulic oil at 207 bar (3,000 psi) for the wash plant. Which prime mover gives the most hydraulic power, and what else does each one bring to a remote Yukon site?

**16–21 kW**
Piston steam engine, condensing · 22–28 hp net

**12 kW**
Old single-stage steam turbine · 16 hp net

**26–31 kW**
$CO_2$ bucket turbine, 500–700 °C · 34–42 hp net

**32–39 kW**
$CO_2$ piston expander, 500–700 °C · 43–53 hp net

## 01 Answer in brief

**Traditional piston steam engine.** It works, and it has real benefits for a remote mine. It runs at low speed (200–600 rpm), so it can drive a hydraulic pump directly. It runs at low pressure (10–30 bar) and is repairable in the field with ordinary shop skills. It also produces **exhaust steam that can thaw frozen gravel and heat wash water**, which is how steam was used in the Klondike fields. But it delivers only about **10 kW non-condensing and 16–21 kW condensing** from the same wood. A piston engine cannot expand steam far enough to use a 5 °C sink, and boiling water at constant temperature matches the 800 °C fire poorly.

**Old traditional steam turbine** (single-stage Curtis / Terry type). It is simple and oil-free, but at this tiny size its efficiency is only about 35 %. Net output is about **12 kW condensing and 8 kW back-pressure**. Its exhaust at 0.08 bar is about **1 m³/s (2,100 cfm)** of vapour, so the condenser is large and must hold a vacuum.

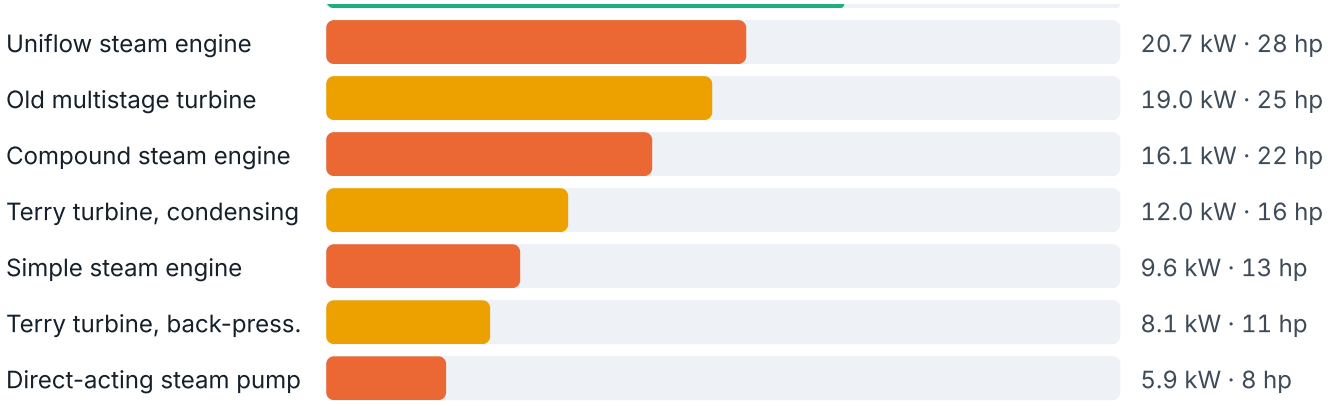
**Infinity Turbine bucket sCO₂ turbine.** With direct-fired $CO_2$ at 500–700 °C it delivers **26–31 kW net** at an assumed 70 % turbine efficiency, or 29–36 kW at 80 %. That is **1.2–1.5 times a modern uniflow steam engine and 1.6–2.0 times a traditional compound engine**, from a machine whose exhaust is about 8 L/s (17 cfm), roughly 1/120 of the steam turbine's. It has no water to freeze and runs at positive pressure, so there is no vacuum to hold.

**$CO_2$ piston expander** (previous study). It still gives the most hydraulic power, **32–39 kW net**, because the plunger pumps oil directly with no gearbox or rotary pump losses. The advantage narrows to about 10 % if both expanders reach the same efficiency (Section 06).

### Net hydraulic power from 500,000 BTU/h of logs




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Net = oil power delivered at 207 bar, after the boiler feed pump or $CO_2$ pump has been driven by a hydraulic motor from the same output. Bar colours: steam piston engine, steam turbine, $CO_2$ bucket turbine, $CO_2$ piston expander.

## 02 Performance comparison

All cases use the same boiler: 146.5 kW (500,000 BTU/h) of wood, 800 °C flue gas, and an economiser or air preheater down to a 150 °C stack. Steam boilers deliver 114.5 kW (391,000 BTU/h) to the steam. Direct-fired $CO_2$ heaters deliver 103.6–111.6 kW, because the flue leaves the coil hotter. Cooling water is 5 °C.

| Prime mover | Inlet | Exhaust / condenser | Shaft kW | Gross hyd. kW | Feed/$CO_2$ pump kW | Net hyd. kW / hp | Oil @ 207 bar L/min / gpm | Wood → net |
|---|---|---|---|---|---|---|---|---|
| **Traditional piston steam engine** | | | | | | | | |
| Simple engine, non-condensing (portable/traction type) | 10 bar, 250 °C 145 psia, 482 °F | atmosphere, 1.1 bar | 10.8 | 9.7 | 0.07 | 9.6 / 12.9 | 28 / 7.4 | 6.6 % |
| Direct-acting duplex steam pump (steam piston → oil plunger, no expansion) | 10 bar, 250 °C | atmosphere | 6.6* | 5.9 | 0.07 | 5.9 / 7.9 | 17 / 4.5 | 4.0 % |
| Traditional compound engine, condensing | 16 bar, 300 °C 232 psia, 572 °F | 0.20 bar, 60 °C | 18.0 | 16.2 | 0.11 | 16.1 / 21.6 | 47 / 12.4 | 11.0 % |
| Modern uniflow engine, condensing (Spilling type) | 30 bar, 400 °C 435 psia, 752 °F | 0.15 bar, 54 °C | 23.3 | 21.0 | 0.19 | 20.7 / 27.8 | 61 / 16.1 | 14.1 % |
| **Old traditional steam turbine** | | | | | | | | |
| Single-stage Curtis / Terry, condensing ($\eta_s$ 35 %) | 30 bar, 400 °C | 0.08 bar, 42 °C | 14.0 | 12.2 | 0.19 | 12.0 / 16.1 | 35 / 9.4 | 8.2 % |
| Same, back-pressure (exhaust steam for thawing) | 30 bar, 400 °C | 1.1 bar, 102 °C | 9.5 | 8.3 | 0.19 | 8.1 / 10.8 | 24 / 6.3 | 5.5 % |
| Old multistage turbine, condensing ($\eta_s$ 55 %) | 30 bar, 400 °C | 0.08 bar, 42 °C | 22.0 | 19.2 | 0.19 | 19.0 / 25.4 | 56 / 14.7 | 13.0 % |
| **Infinity Turbine bucket s$CO_2$ turbine ($\eta_s$ 70 %), gearbox + hydraulic pump** | | | | | | | | |
| Direct-fired, recommended temperature | 200 bar, 500 °C 2,900 psia, 932 °F | 45 bar, 10 °C | 41.4 | 35.4 | 8.3 | 25.6 / 34.4 | 103 / 27.1 | 17.5 % |
| Direct-fired, 800 °C flue | 300 bar, 700 °C 4,350 psia, 1,292 °F | 45 bar, 10 °C | 50.9 | 43.5 | 10.3 | 31.4 / 42.1 | 126 / 33.3 | 21.4 % |
| **$CO_2$ piston expander (η 80 %), direct hydraulic plungers (previous study)** | | | | | | | | |
| Direct-fired, recommended temperature | 200 bar, 500 °C | 45 bar, 10 °C | 45.1 | 41.5 | 7.9 | 32.2 / 43.2 | 120 / 31.8 | 22.0 % |
| Direct-fired, 800 °C flue | 300 bar, 700 °C | 45 bar, 10 °C | 55.1 | 50.7 | 9.8 | 39.2 / 52.6 | 147 / 38.8 | 26.8 % |

*Indicated work equivalent; a direct-acting pump has no shaft. Oil flow is the gross hydraulic flow before the pump-drive motor takes its share. "Wood → net" = net hydraulic power ÷ 146.5 kW of fuel.

# 03 Traditional piston steam engine

## Why it produces less power

- **It cannot use the cold creek water.** At 5 °C cooling, steam could condense at 15 °C. At that point a kilogram of steam occupies about 77 m³. A piston engine sweeps a fixed volume, so in practice it stops expanding near 1 bar (overall expansion ratio 8–15) and drops the rest of the pressure across the exhaust valve as a loss.
- **Boiling at one temperature wastes the fire's temperature.** Water boils at 201 °C (16 bar) or 234 °C (30 bar) no matter how hot the fire is. More than 70 % of the heat goes in at that one low temperature. Supercritical $CO_2$ heats smoothly up to 500–700 °C and follows the cooling flue gas closely.
- **Losses inside the cylinder.** Steam condenses on the cylinder walls and loses heat to them. Clearance volume and valve throttling also cost work. The diagram factor is 0.70–0.82, and mechanical efficiency is about 0.88.

## Real benefits for a Yukon placer mine

- **Low speed, high torque:** 200–600 rpm drives a hydraulic gear or piston pump directly or through a belt. No high-speed gearbox is needed.
- **Proven and field-repairable:** cast-iron cylinders, slide or poppet valves, babbitt bearings. More than 150 years of operating knowledge, and spare parts can be made in a mine machine shop.
- **Low pressure:** 10–30 bar (145–435 psi), against 200–300 bar for $CO_2$.
- **Exhaust steam is useful:** run non-condensing and the 153 kg/h (340 lb/h) of exhaust steam at about 100 °C can **point-thaw frozen gravel** or heat sluice and wash water. That is combined heat and power the $CO_2$ machines cannot offer as directly.
- **Direct-acting steam pumps** (Worthington duplex type) are the historical version of our $CO_2$-piston-to-oil-plunger idea. They are very simple, but they run without expansion, so they are inefficient (5.9 kW).

**Drawbacks in the Yukon**

- **Freezing:** boiler, condenser and lines full of water at −40 °C. Every shutdown in the cold season needs a full drain-down, or heat tracing and an antifreeze-protected condenser.
- **Water treatment:** a non-condensing engine consumes about 3.7 t/day (980 US gal/day) of make-up water, which must be softened and deaerated or the boiler scales.
- **Condensing needs a vacuum:** a 0.15–0.20 bar condenser needs an air ejector or vacuum pump and constant leak hunting.
- **Operator certification:** steam plants in Canadian jurisdictions are commonly subject to boiler-operator / power-engineer certification. Check the Yukon Boilers and Pressure Vessels requirements before choosing steam.
- **Lubrication:** cylinder oil ends up in the condensate and must be separated before the water returns to the boiler.

## Steam engine summary

| Variant | Net hyd. | Steam flow |
|---|---|---|
| Simple non-condensing | 9.6 kW · 12.9 hp | 153 kg/h · 338 lb/h |
| Compound condensing | 16.1 kW · 21.6 hp | 148 kg/h · 327 lb/h |
| Uniflow condensing | 20.7 kW · 27.8 hp | 137 kg/h · 303 lb/h |

# 04 Old traditional steam turbine

Small mechanical-drive turbines of the 1900s–1960s had either a single-stage Curtis (two velocity rows) or a Terry "re-entry bucket" wheel. In a Terry wheel, steam is jetted into semicircular buckets, turned back through reversing chambers and re-entered several times. That makes it the closest historical relative of the bucket $sCO_2$ turbine. They were built to be reliable, not efficient: at 10–50 kW, the isentropic efficiency is typically 25–40 %.

- **Condensing (0.08 bar, 42 °C):** 14.0 kW shaft, **12.0 kW net hydraulic**. The 5 °C water allows a deep vacuum, but the turbine is too inefficient to convert it into much work.
- **Back-pressure (1.1 bar):** 8.1 kW net, with about 139 kg/h (306 lb/h) of exhaust steam available for thawing.
- **Old multistage (η 55 %):** 19.0 kW net, close to a good piston engine, but rare and expensive at this size.

### Practical points

- Speed of 3,600–6,000 rpm (Terry) or up to 30,000 rpm (de Laval) needs a reduction gearbox (≈ 97 %) before the hydraulic pump.
- No lubrication touches the steam, so the condensate stays clean. Few parts wear, and it tolerates wet steam better than modern turbines.
- Condensing exhaust is about **1.0 $m^3/s$ (2,100 cfm)** at 0.08 bar. The condenser and exhaust duct are bulky, and air leaks degrade the vacuum.
- It has all the freezing, water-treatment and certification issues of the steam engine.

# 05 Infinity Turbine bucket $sCO_2$ turbine

The inflow bucket radial turbine (two-stage for Rankine $CO_2$) uses the same direct-fired, recuperated transcritical cycle as the piston expander, with 5 °C cooling and condensing at 10 °C / 45 bar. The turbine shaft drives a variable-displacement axial-piston hydraulic pump through a reduction gearbox (gear 95 % × pump 90 %). A high-speed alternator feeding electric motor-pumps is the alternative (≈ 92 % × 90 % × 90 %), and is useful where power must be spread around the site.

| Bucket turbine efficiency | 500 °C / 200 bar | 700 °C / 300 bar |
|---|---|---|
| 60 % (first prototype) | 21.6 kW · 29.0 hp | 26.7 kW · 35.8 hp |
| **70 % (base case)** | **25.6 kW · 34.4 hp** | **31.4 kW · 42.1 hp** |
| 80 % (developed two-stage) | 29.3 kW · 39.3 hp | 35.7 kW · 47.8 hp |

Base case at 500 °C: $CO_2$ 0.32 kg/s (2,540 lb/h); turbine exhaust 8.4 L/s (17.7 cfm) at 46 bar and 373 °C, which then passes through the recuperator; shaft 41.4 kW (55.5 hp).

## Strengths

- **1.2–1.5× the hydraulic power of a modern uniflow steam engine**, and 1.6–2.0× a traditional compound engine, from the same wood.
- **Compact:** exhaust volume about 1/120 of a condensing steam turbine and 1/7 of a steam engine's release volume. No vacuum system.
- **Hot end without rubbing seals:** unlike the piston expander, there are no piston rings sliding at 500–700 °C. Only the wheel and nozzles are hot, which makes 700 °C operation more realistic.
- **Continuous flow:** no pulsation, and no valve gear to time or wear.
- **No water:** nothing to freeze at −40 °C and no water treatment. $CO_2$ is non-flammable and stable.
- Fits the Cluster Mesh roadmap: the same turbine family scales by numbering-up for larger mines.

## Weaknesses

- High speed needs a gearbox or high-speed generator. A failure needs factory repair rather than mine-shop repair.
- 200–300 bar $CO_2$ throughout. Efficiency at this power level is still to be proven on the lab cart.

# 06 Bucket turbine vs $CO_2$ piston expander

Both $CO_2$ machines share the same cycle, so the difference comes from two places:

1. **Coupling to the oil:** the piston pushes oil directly (92 %). The turbine needs a gearbox and a rotary pump (≈ 85.5 %).
2. **Expander efficiency:** the piston study assumed 80 %. A hot, ring-sealed piston expander with blow-by and valve losses may well come in nearer 70 %.

Compared at the same expander efficiency, the gap closes to about 10 %:

| Both at 70 % expander efficiency | 500 °C / 200 bar | 700 °C / 300 bar |
|---|---|---|
| $CO_2$ piston expander | 28.3 kW | 34.7 kW |
| $CO_2$ bucket turbine | 25.6 kW | 31.4 kW |

### Which $CO_2$ expander for the mine?

- **Piston expander:** best if the only output is hydraulic power and the $CO_2$ stays at about 500 °C. It runs at low speed, has no gearbox, and has the highest net output.
- **Bucket turbine:** best at 600–700 °C (no hot sliding seals), when continuous smooth power or electricity is also wanted, and when the turbine is a product that will be built in volume.
- Both beat every steam option by a wide margin. Steam's advantages are field repairability and thaw steam, not power.

## 07 Site suitability matrix

| Criterion | Piston steam engine | Old steam turbine | $CO_2$ bucket turbine | $CO_2$ piston expander |
|---|---|---|---|---|
| Net hydraulic power (from 500,000 BTU/h) | 10–21 kW | 8–19 kW | **26–36 kW** | **32–39 kW** |
| Operating pressure | 10–30 bar | 30 bar | 200–300 bar | 200–300 bar |
| Freezing at −40 °C | Drain-down needed | Drain-down needed | No water | No water |
| Water treatment / make-up | Yes (3.7 t/day non-cond.) | Yes | None | None |
| Vacuum system | If condensing | Yes, 1 $m^3$/s exhaust | No (45 bar) | No (45 bar) |
| Speed / drive to hydraulic pump | 200–600 rpm, direct | Gearbox | Gearbox / HS alternator | Direct plunger |
| Field repair at the mine | Excellent | Good | Swap unit, factory repair | Moderate (hot valves, rings) |
| Useful by-product heat | Thaw steam ~100 °C | Thaw steam (back-pressure) | Glycol at 8–40 °C | Glycol at 8–40 °C |
| Size of machinery | Large | Large condenser | **Smallest** | Small–medium |
| Technology maturity | Mature | Mature (used / surplus) | Development (lab cart) | Development |

## 08 Conclusions

### Steam is proven but delivers about half the power; the $CO_2$ machines win on power, cold-climate operation and size

- A **traditional piston steam engine** gives 10 kW non-condensing or 16–21 kW condensing. Its real benefits are low speed, low pressure, field repairability and thaw steam. Freezing, water treatment and operator certification count heavily against it in the Yukon.
- An **old steam turbine** is the weakest option at this size: 12 kW condensing or 8 kW back-pressure, unless a rare multistage unit is found (19 kW).
- The **bucket sCO₂ turbine** gives 26–31 kW at 70 % efficiency (up to 36 kW at 80 %). That is 1.2–1.5× the best steam engine and 1.6–2.0× a traditional compound engine, with no water, no vacuum and the smallest machinery. At 700 °C it is more practical than the piston expander because nothing slides at the hot end.
- The **$CO_2$ piston expander** remains the top hydraulic producer at 32–39 kW, because it couples directly to the oil.
- One option worth keeping: a **small back-pressure steam bleed or a separate thaw boiler** alongside a $CO_2$ power unit, if ground thawing is a site requirement.

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## 09 Basis and assumptions

| Parameter | Value used |
|---|---|
| Fuel / boiler | 500,000 BTU/h (146.5 kW) logs; 800 °C flue; 5 % casing loss; 150 °C stack with economiser/air preheater. Steam boilers 78.2 % to steam; direct-fired $CO_2$ heaters 70.7–76.2 % (hotter coil exit) |
| Cooling | 5 °C creek/glycol water. Steam condensers at 0.08–0.20 bar (practical vacuum); $CO_2$ condensing 10 °C / 45 bar |
| Steam piston engines | Incomplete-expansion (modified Rankine) model with expansion ratios 5 / 10 / 15. Diagram factor 0.70 / 0.75 / 0.82; mechanical 0.88 |
| Direct-acting steam pump | Full admission, no expansion; 0.85 diagram factor |
| Steam turbines | Isentropic 35 % (single-stage Curtis/Terry), 55 % (old multistage); gearbox 97 % |
| $CO_2$ bucket turbine | Isentropic 70 % (60–80 % sensitivity); gearbox 95 %; recuperator 10 K pinch; high pressure optimised (≤ 200 or 300 bar) |
| $CO_2$ piston expander | 80 % indicated (70 % sensitivity); piston → oil 92 % |
| Hydraulic | Rotary hydraulic pump 90 %; feed/$CO_2$ pump driven by hydraulic motor at 85 %; system 207 bar (3,000 psi) |
| Properties | CoolProp 8: IAPWS-95 water/steam, Span–Wagner $CO_2$ |

The efficiencies for historical steam machinery and the bucket turbine are engineering estimates for machines of this size, not test data. The comparison is preliminary and for feasibility only.

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