



Spinning Up, Not Out

Scaling the Turbomachinery Supply Chain
for Rapid Geothermal Deployment



MARCH 2026

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for Rapid Geothermal Deployment



**New
System
Ventures**

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Kelsi Katcher, a lead engineer in the Rotating Machinery Development Section at Southwest Research Institute (SwRI), was also an invaluable contributor to the sections of this paper focused on improving energy efficiency, reliability, and affordability through turbomachinery component and system design, analysis, and testing.

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Definitions

Air-cooled condenser (ACC): A condenser that rejects heat directly to ambient air without evaporative water use.

Balance of plant (BOP): All non-power-block systems, including cooling, piping, electrical yard, and civil works.

Binary plant: A geothermal plant in which reservoir fluid heats a separate closed-loop working fluid.

Brayton cycle: A gas-phase thermodynamic cycle based on compression, heating, expansion, and cooling.

Breakbulk: Shipment of large or heavy equipment outside standard containers as individual cargo pieces.

Condenser: The heat exchanger that removes heat from the working fluid and returns it to liquid or near-liquid state.

Critical point: The temperature and pressure at which a fluid no longer exhibits distinct liquid and gas phases.

Evaporator/vaporizer: The heat-exchanger section where the working fluid reaches its vapor expansion condition.

Flat rack: An open container platform used to transport oversized or heavy cargo.

Form factor: The physical size and configuration of a power block relative to its output rating.

Geothermal brine: Produced reservoir fluid used as the plant heat source.

Heat exchanger: Equipment that transfers heat between fluids without mixing them.

Hybrid cooling: A cooling configuration that combines dry and wet heat-rejection methods.

Installed capital expenditure (CapEx): The total cost to procure, transport, construct, and commission a plant.

Lead time: The period between equipment order placement and delivery readiness.

Levelized cost of electricity (LCOE): The life cycle average cost per unit of electricity generated.

Modularization: Factory fabrication of transportable plant sections for field assembly.

Nameplate capacity: The rated electrical output under specified design conditions.

Operations and maintenance (O&M): The ongoing activities and costs required to operate and service the facility.

Organic Rankine Cycle (ORC): A closed-loop Rankine cycle using an organic working fluid heated indirectly by geothermal brine.

Original equipment manufacturer (OEM): A firm that designs, fabricates, and warrants major plant equipment or integrated packages.

Out-of-gauge (OOG) cargo: Equipment shipments exceeding standard container dimensional limits.

Parasitic load: On-site electrical consumption required to operate plant systems.

Power block: The integrated thermodynamic equipment that converts heat into shaft and electrical power.

Rankine cycle: A liquid–vapor thermodynamic cycle based on pressurization, boiling, expansion, and condensation.

Recuperator: An internal heat exchanger that transfers turbine exhaust heat to the compressed working fluid.

Subsurface: Wells, casing, downhole equipment, and the geothermal reservoir.

Supercritical carbon dioxide (sCO₂) cycle: A carbon dioxide (CO₂) Brayton cycle operating fully above the CO₂ critical point.

Topsides: All above-ground equipment that converts geothermal heat into electricity, excluding wells and reservoir infrastructure.

Trans-critical carbon dioxide (tCO₂) cycle: A CO₂ cycle that crosses the critical point during cooling or compression.

Turbine/expander: A rotating machine that converts fluid energy into mechanical shaft power.

Turbo-generator module: A factory-assembled turbine and generator package mounted on a transportable base.

Wet cooling: A heat-rejection method that uses evaporative water cooling.

Working fluid: The closed-loop fluid circulating within the power cycle (organic fluid in ORC systems or CO₂ in CO₂ cycles).



Executive Summary

Spinning Up Without Spinning Out: The Near-Future Turbomachinery Constraint

AI DEMAND AND SPEED-TO-POWER

Throughout 2025, headlines called out the massive energy demand coming from the need for more data centers. Plans for multi-gigawatt data center campuses have emerged across the United States and internationally.¹ A recent Goldman Sachs Research report projected that by 2030, global power demand from data centers will rise by 165%.² In response, the White House announced its Speed to Power Initiative last fall to accelerate large-scale generation and grid infrastructure projects.³

The International Energy Agency's (IEA's) 2024 assessment puts global next-generation geothermal potential at a minimum of 800 gigawatts-electric (GWe) by 2050.⁴ An analysis by Rhodium Group of enhanced geothermal potential suggests these systems could economically meet up to 64% of projected U.S. data center demand growth by the early 2030s.⁵ If data centers are located near optimal geothermal resources, these systems have

Because data centers need reliable power 24 hours per day, hyperscalers have increasingly shifted to baseload power that can be stabilized and supplemented with variable renewable energy.

the potential to meet all projected demand growth at a stable and low cost, in part because geothermal is dispatchable and modular and can be co-located with data centers—which helps avoid interconnection delays.

Today, the immediate need is for multi-gigawatt baseload power for hyperscale and artificial intelligence (AI) data centers—and companies are prepared to pay extra for reliable, on-site supply. U.S. data centers alone are projected to need between 41 GW and 156 GW of additional capacity by 2030. Under high AI-adoption scenarios, those amounts represent between 13% and 38% of total U.S. electricity consumption.⁶

GROWTH PROJECTIONS FOR U.S. DATA CENTERS' ENERGY DEMANDS

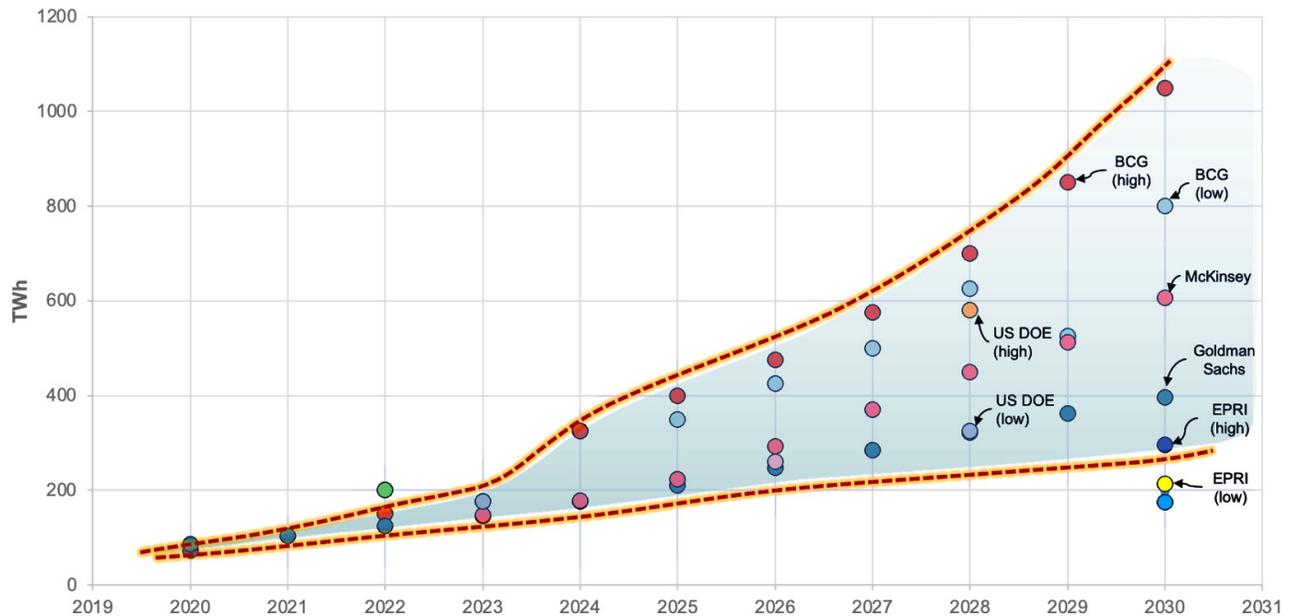


Figure 1: The combined growth projections for energy demand from data centers in the United States. BCG = Boston Consulting Group; DOE = Department of Energy; EPRI = Electric Power Research Institute; TWh = terawatt-hours. Source: Adapted from Yusifov, M., & Enriquez, N. (2025). *From core to code: Powering the AI revolution with geothermal energy*. Project InnerSpace.

BASELOAD SUPPLY WITH NEXT-GENERATION GEOTHERMAL SYSTEMS

Enormous shifts in energy demand are also changing requirements for electrical grids.⁷ Data centers create massive, almost instantaneous fluctuations in energy load. While most facilities currently rely on grid power with on-site backup generation, growing grid constraints and interconnection delays are driving hyperscalers to pursue dedicated primary power generation at the point of consumption. Because data centers need reliable power 24 hours a day, hyperscalers have increasingly switched to baseload power that can be stabilized and supplemented with variable renewable energy via the grid. The problem is that traditional grid interconnection timelines create bottlenecks, prompting a shift to “bring your own power” models—hyperscalers develop generation assets behind the meter dedicated solely to the data center or, at the very least, pledge to avoid increasing consumer energy costs.⁸

The ideal power-generating asset would be a domestic, low-carbon solution with a high capacity factor.

Nuclear energy appears to fit this profile in theory, yet construction and regulatory timelines make it inaccessible for near-term needs. Because of immediate needs, hyperscalers have largely relaxed their low-carbon goals. Most major data center projects, for example, are being developed to be powered with natural gas turbine plants. This approach for power is not likely to meet the need for fast growth and scale of the industry, as natural gas turbine supply chain delays are causing lead times of five years or longer.⁹

The urgency, combined with a desire for domestic and decarbonized energy, is driving interest by industry, startups, and government in next-generation geothermal, which generates electricity from subsurface heat. Unlike conventional geothermal, which has been produced for decades in places like

Next-generation geothermal systems represent a credible path to secure, domestic baseload power.

Iceland and is relatively rare in terms of geological conditions in the world, next-generation geothermal engineers the subsurface to create the conditions needed to harvest geothermal energy. Deep directional drilling, stimulation technologies, novel well completion techniques, and novel working fluids are examples of engineering approaches that are dramatically expanding the geographic potential of geothermal energy by decoupling power generation potential from naturally occurring "Goldilocks" geological conditions.

Geothermal offers the same 24/7 baseload profile as nuclear or natural gas. Unlike intermittent renewables, geothermal can provide firm capacity; unlike natural gas, it delivers power without ongoing operational carbon supply chain disruption or constraint risk and is not dependent on a continuous fuel supply. Next-generation systems represent a credible path to secure, domestic baseload power.

***From Core to Code: Powering the AI Revolution with Geothermal Energy,*¹⁰ underscores geothermal's value: dispatchable, modular, and capable of co-locating with data centers to avoid interconnection delays. Added to that value is the potential to leverage geothermal resources for direct cooling—which historically represents between 30% and 40% of data center load.**

GEOHERMAL TURBOMACHINERY AND PATHS TO SCALE

Recent geothermal contracts with companies in the geothermal turbomachinery industry point to a development pipeline that exceeds 600 megawatts-electric (MWe) in fields with operating temperatures

As drilling costs fall, topside surface systems (such as heat exchangers and turbines that generate electricity) will collectively account for 40% to 50% of total project costs and much of the risk of delays. Yet, these systems remain under the radar of investors, and the industry at large remains technologically stagnant, lacking demand signals that would spur competition, innovation, and growth.

above 200°C.^{11,12} Fervo Energy is poised to deliver 100 megawatts (MW) of baseload power in 2026 and an additional 400 MW by 2028. Analysts project there will be more than 800 GWe of global next-generation geothermal system capacity by 2050.¹³ If fully realized, that amount could supply up to 20% of U.S. electricity generation and meet 15% of global electricity demand growth. A critical question remains: **What infrastructure, policy, and manufacturing investments are required to realize and expedite this trajectory?**

Those timelines could be reduced by leveraging U.S. gas-turbine and aerospace production infrastructure to manufacture turbine and heat-exchanger systems.

Drilling innovations and subsurface work have dominated discussions of geothermal development.^{14,15} As drilling costs fall, topside surface systems, such as heat exchangers and turbines that generate electricity, will collectively account for 40% to 50%¹⁶ of total project costs and much of the risk of delays. Yet, these systems remain under the radar of investors, and the industry at large remains technologically stagnant, lacking demand signals that would spur competition, innovation, and growth.

Advances in turbomachinery production, Organic Rankine Cycles (ORCs), and other cycles such as supercritical carbon dioxide (sCO₂) or trans-critical CO₂ (tCO₂) systems could unlock major performance and geothermal cost improvements. ORC systems are proven, financeable, and available at the 50+ MWe scale; they primarily require additional manufacturing capacity expansion. Additionally, as the industry moves toward the production of fluid at high surface temperatures, with wells above 250°C in Utah¹⁷ and Oregon¹⁸ that need binary-cycle systems, other working fluids such as sCO₂ and tCO₂ turbines offer compactness and modularity, enabling faster on-site installation and potential cost reductions once components become standardized.

Turbomachinery components are mostly manufactured outside the U.S., resulting in extended logistics and delivery lead times (12 months to 18 months). Those timelines could be reduced by leveraging U.S. gas-

To reach the geothermal industry's potential requires simultaneous advancement in two areas: (i) continued subsurface progress and (ii) a fundamental shift toward standardized, domestically manufactured turbomachinery that can be delivered at scale.

turbine and aerospace production infrastructure to manufacture turbine and heat exchanger systems. Policy mechanisms such as the U.S. Department of Commerce's Investment Accelerator that structure global trade deals into domestic manufacturing investments could reduce risks of industry overbuilding, expand U.S. jobs, and ensure a steady supply for low-cost baseload geothermal power operations. In the long term, providing a domestic supply base for turbomachinery parts allows geothermal project developers to benefit from federal tax credits for domestic content procurement, leading to improved unit economics at a plant level. Finally, advances in manufacturing could also reduce material requirements and enable greater component standardization across geothermal installations.

While the next technical frontier for geothermal lies in accessing deeper or hotter resources, which will increase power per well and therefore investment return profiles, the surface systems (balance of plant management, heat exchangers, cooling, power electronics, auxiliary systems, and especially turbines) will increasingly determine a project's timeline and overall economics.

To reach the geothermal industry's potential requires simultaneous advancement in two areas: (i) continued subsurface progress and (ii) a fundamental shift toward standardized, locally manufactured turbomachinery that can be delivered at scale.

The core technologies needed to enable this transition across the U.S. and its allied industrial ecosystem are already in place. What's missing are effective coordination—specifically strong market signals that align demand for high-temperature geothermal, alongside capital investment, financing mechanisms, and policy support.

GEOTHERMAL ENERGY PRODUCTION COSTS

Surface Side as the Next Cost Frontier

While subsurface drilling has rapidly declined in cost through the adoption of oil and gas technology,¹⁹ the same reductions have not yet happened for surface-side systems. Technology and knowledge transfer have benefited subsurface cost curves, but surface systems remain stuck on an early learning curve.²⁰ Geothermal uses different turbines, heat exchangers, condensers, and cooling systems than other power production methods, so developers historically have taken a more custom project-by-project approach. What's more, the global manufacturing base remains concentrated among a small number of original equipment manufacturers (OEMs) that have relatively limited incentives to expand production capacity or pursue economies of scale. The current rough cost rule of thumb is \$3 million per MWe without engineering, procurement, and construction (EPC) and \$4 million per MWe with EPC for ORC topsides.²¹ Further cost reductions in geothermal development will increasingly depend on surface plant innovation and manufacturing optimization rather than continued subsurface advances alone.

Behind-the-meter configurations can offer a solution by bypassing traditional interconnection processes and enabling the direct coupling of generation assets to load centers—such as a data center.

Co-location and Behind-the-Meter Considerations

Although co-locating a geothermal power plant with a data center is attractive for hyperscalers, a developer has to consider the factors that affect both the surface-side performance and subsurface favorability.

Binary-cycle plant output and efficiency depend on site-specific conditions that may change from season to season. For example, as air temperatures rise, condenser performance and overall power output drop. Typical ORCs achieve thermal-to-electric efficiency ranging from 10% to 25%,^{22,23} meaning that roughly between 75% and 90%

of the extracted heat must be rejected from the system. Air cooling minimizes water use, but output is lower during periods with hot ambient conditions. Water-cooling systems perform better but add more complexity for permitting and infrastructure build-out. These climate-dependent trade-offs directly influence siting decisions and are particularly material for behind-the-meter installations, where reliability and delivered capacity must remain consistent.

Grid interconnection issues can also delay and complicate siting; at times, it can take up to five years for some components to be delivered. Behind-the-meter configurations can offer a solution by bypassing traditional interconnection processes and enabling the direct coupling of generation assets to load centers—such as a data center. This approach has gained traction among offtakers who require accelerated deployment (6 months to 18 months).

This analysis finds that without thoughtful intervention, surface equipment will remain the binding constraint on geothermal deployment velocity and project economics, regardless of how far subsurface costs fall. The geothermal turbomachinery supply chain is concentrated among a handful of OEMs, largely dependent on international manufacturing, and structured around custom, project-by-project procurement, a model incompatible with the scale and speed the market now demands. Today's turbine production is largely defined by project-by-project design, limited standardization, and a thin supplier base with long research and innovation cycles—conditions that inhibit mass production and suppress innovation.

Yet, a clear opportunity is emerging: Turbine manufacturing can unlock significant growth by developing new product lines tailored to high-temperature heat-to-power conversion systems in the 200°C to 300°C (and higher) range—which is critical for next-generation geothermal's economic viability. Advancing these technologies, however, requires a firm, clear aggregated demand signal to justify capital investment in manufacturing capacity and product development. Without that signal, the sector remains trapped in a low-volume existence.

Uprighting this imbalance requires coordinated action across three fronts: standardizing ORC and next-generation turbine designs—and making them modular—to enable factory-built, repeatable power blocks; expanding domestic manufacturing capacity by leveraging existing gas turbine and industrial turbomachinery facilities; and shaping demand through advance market commitments and performance-based procurement that will give manufacturers the ability to invest in capacity.



Steam turbine under maintenance

Chapter 1

Topsides 101: Technical Characteristics and Performance Trade-offs of Surface Plant Systems

THE FLASH VS. BINARY DISTINCTION IN GEOTHERMAL

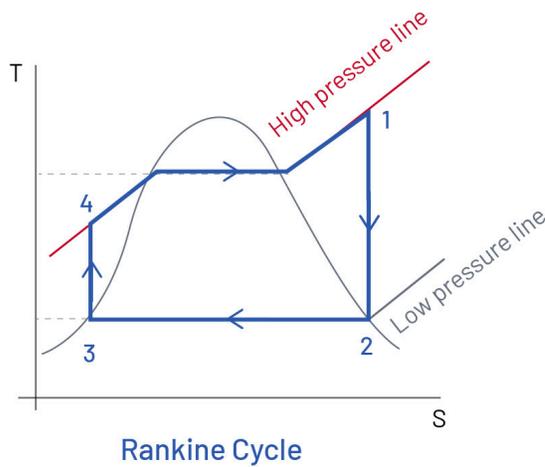
To produce electricity from geothermal energy, historically **flash systems** have been used in which hot brine from a reservoir undergoes a controlled phase change on surface in a flash tank or separator, and the steam is then directed through the power turbine. As the hot, high-pressure steam expands, it spins the turbine blades, producing mechanical energy that drives an electrical generator. Flash systems and steam turbines are mainly suited to conventional hydrothermal reservoirs with naturally high temperatures, high pressures, and favorable fluid conditions. Due to differences in technologies and heat production conditions that will be considered further in the following pages, these systems are not expected to be the dominant architecture for future large-scale geothermal deployment.

In next-generation geothermal systems, water is injected into engineered fracture networks where it absorbs

heat from the rock. It's then recovered at the surface. Because the produced fluid starts as injected water rather than from a naturally pressurized hydrothermal reservoir, flash conversion is impractical. This means **binary systems** are the primary architecture for next-generation surface facilities (the "topsides"). These systems use a dual-loop configuration in which geothermal brine remains isolated from the power-generation equipment (**Figure 3**). The brine produced from the reservoir transfers thermal energy through a heat exchanger to a secondary working fluid, typically an organic compound with a substantially lower boiling point than water, which then vaporizes and expands through the turbine to generate electricity. This approach enables power generation from lower-temperature subsurface resources while preventing direct exposure of turbomachinery to corrosive or scaling geothermal fluids.

The most common implementation of this concept in geothermal is the Organic Rankine Cycle turbine, or ORC, in which the secondary fluid is an organic compound such

RANKINE CYCLE TEMPERATURE ENTROPY DIAGRAM



The ideal Rankine cycle on a temperature-entropy (T-s) diagram

- 1→2: Isentropic expansion across turbine (high to low pressure)
- 2→3: Constant pressure condensation (gas to liquid phase)
- 3→4: Pump work input (low to high pressure)
- 4→1: Constant pressure heat addition (liquid to superheated gas)

Figure 2: An ideal Rankine cycle. Source: Reddy, V. S., Kaushik, S. C., Tyagi, S. K., & Panwar, N. (2010). [An approach to analyse energy and exergy analysis of thermal power plants: A review](#). *Smart Grid and Renewable Energy*, 1(3), 143–52.

as a pentane derivative or another common refrigerant. The thermodynamic performance of these systems is governed by the closed-loop Rankine cycle.

Today, binary systems are also commonly deployed in conventional geothermal applications, especially in locations where the produced brine is highly mineralized or corrosive—or both.

THE CLOSED-LOOP RANKINE CYCLE

The Rankine cycle is one of the fundamental thermodynamic cycles in which heat is converted into mechanical work. At the base level, a Rankine cycle contains a turbine, a condenser (e.g., cooler or heat rejection), a pump, and an evaporator (e.g., heat addition). The cycle is considered to be closed-loop, meaning the total mass in the system is constant, mass flow through each piece of equipment is the same, and no mass enters or leaves the system. See **Figure 2** for the ideal Rankine cycle presented on the temperature-entropy diagram.

HOW A CLOSED-LOOP RANKINE CYCLE WORKS

1. Fluid entering the cycle is expanded across the turbine from state point 1 to state point 2. In this step, the fluid drops from the high-pressure line to

the low-pressure line. In the ideal cycle, this step is considered isentropic (there are no inefficiencies due to an increase in entropy).

2. The fluid is then condensed as heat is rejected (point 2 to point 3). During this step, the state point of the fluid moves left across the vapor dome, meaning the working fluid is changing from the gas phase to the liquid phase. This step is considered to be constant pressure (no pressure losses through the heat exchanger).
3. Once in the liquid phase, the fluid is pumped from the low-pressure line back up to the high-pressure line (point 3 to point 4). Here, mechanical work is input at the pump to increase the energy state and pressure of the fluid.
4. Finally, the fluid is heated across the heat exchanger (point 4 to point 1). The high-pressure liquid is heated back across the vapor dome to the superheated-gas phase. The purpose of the heat exchanger is to increase the amount of energy in the working fluid that can be converted into mechanical energy.

GEOHERMAL BRINE

Central to these processes is the hot geothermal fluid that is produced from the reservoir (**Figure 3**). On the surface, the brine (which is mostly water with some dissolved minerals from the subsurface, which makes the fluid salty) is directed through a heat exchanger. As mentioned, the heat from the brine is transferred to the power cycle

working fluid. After the brine leaves the heat exchanger, its temperature is much cooler, and the brine returns to the geothermal reservoir through a reinjection well.

Because of the relatively low source temperature, only 10% to 20% of the thermal energy entering the power cycle converts to electricity. The rest must be rejected as low-grade heat to maintain system operation. This heat-rejection requirement drives one of the most consequential design decisions in geothermal surface plants: the configuration of the cooling system.

Air cooling reduces water use, meaning the installation does not need to be located near a continuous source of fresh water, but the efficiency of the cooling process is at the mercy of ambient temperatures that raise condensing temperatures during hot periods and cut net output. Wet cooling improves annual power generation but requires water sourcing and permitting. Hybrid configurations and improved air-cooled designs offer better heat exchange surfaces, wind management, modest evaporative assistance, and anticipatory controls, thus mitigating performance degradation during peak temperature intervals.

HEAT BALANCE THROUGH A GEOTHERMAL BINARY PLANT

The heat we produce from a geothermal reservoir is a critical piece of the plant's power-generation potential: The higher the produced temperature, the more power can be generated.

The Carnot cycle efficiency is a useful framework for understanding power plants' potential. The Carnot efficiency is an idealized, theoretical thermodynamic cycle used to represent the maximum possible efficiency at which a power cycle can convert thermal energy into mechanical energy—as defined by the hot reservoir and cold reservoir temperatures. This efficiency can be calculated using the equation in **Figure 4**. Installed power cycles always operate with an efficiency below the Carnot efficiency.

Considering the target temperature range for produced fluid for next-generation geothermal systems (200°C–300°C), the maximum energy conversion that is theoretically possible is between 36% and 47%, depending on the heat-rejection temperature.

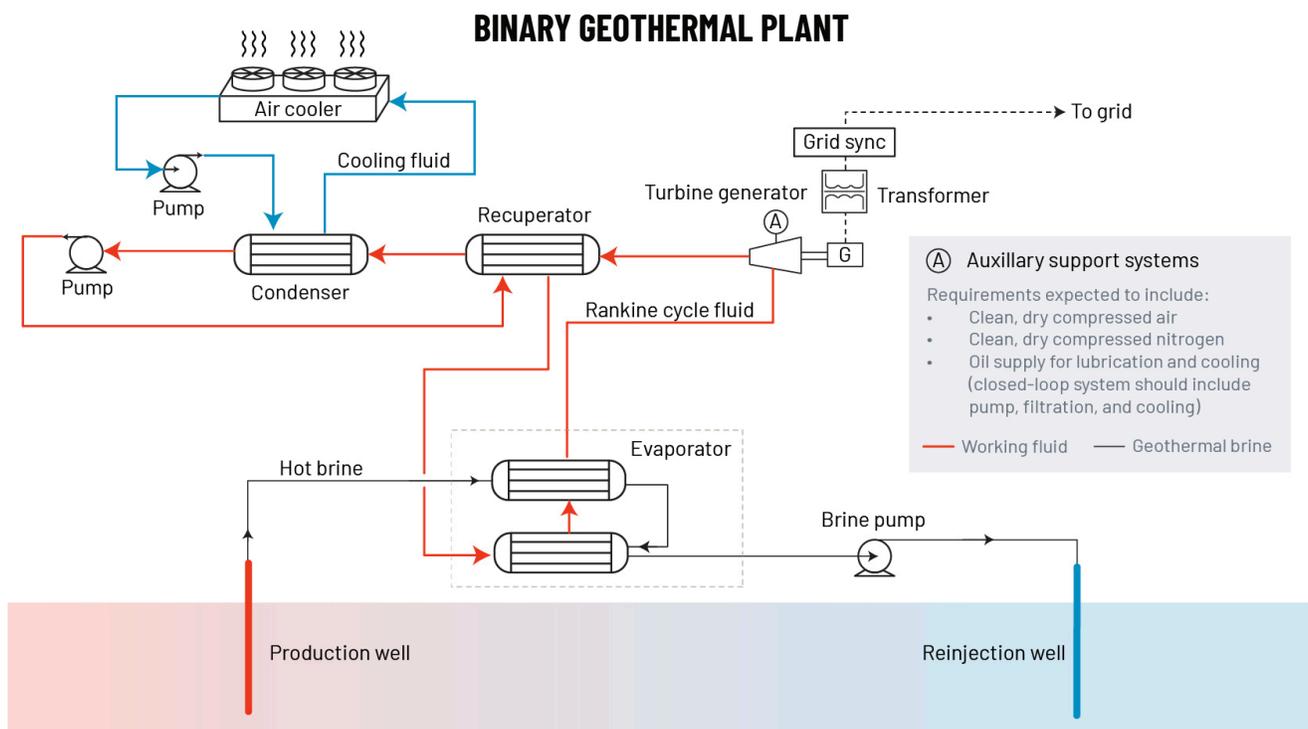


Figure 3: Example schematic of a closed-loop Organic Rankine Cycle (ORC) applied to a geothermal source. Source: SwRI, 2025.

CARNOT EFFICIENCY EQUATION

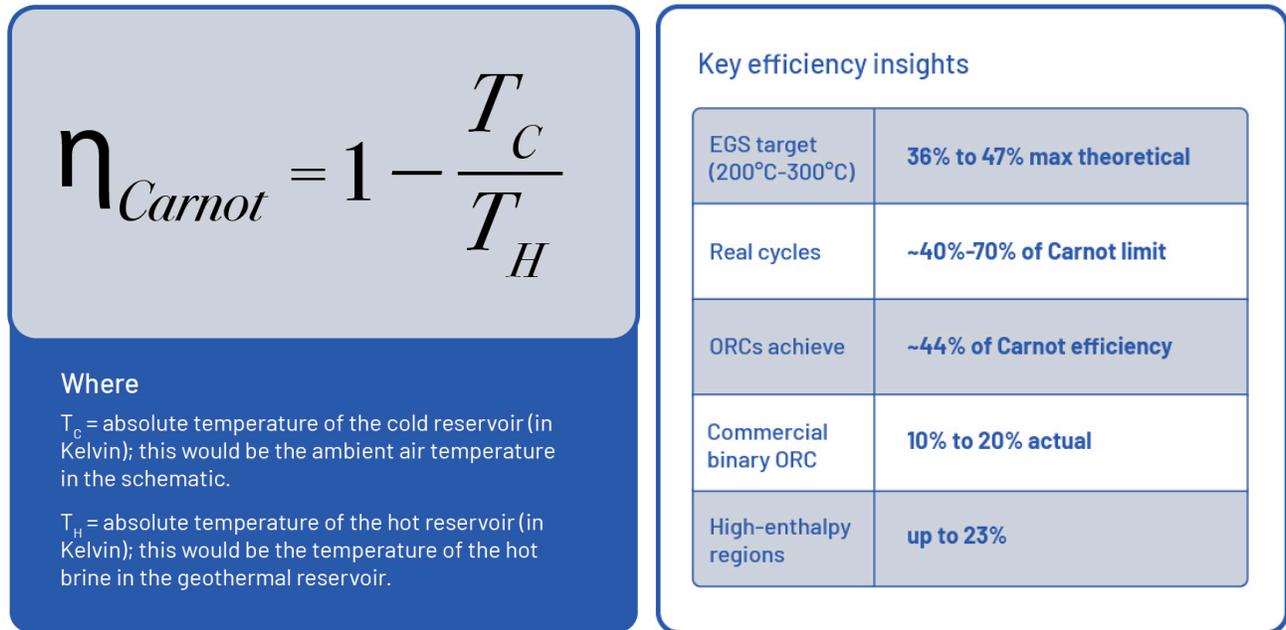


Figure 4: Carnot efficiency equation. EGS = engineered geothermal system; ORC = Organic Rankine Cycle.

Most installed power cycles tend to operate at approximately 40% to 70% of their Carnot limit. In a review of ORCs, overall heat-to-electric conversion tends to be approximately 44% of the Carnot efficiency.²⁴ As mentioned, actual cycle efficiencies for commercially available binary ORC systems generally range from 10% to 20%, requiring high-enthalpy sources to reach higher cycle efficiencies.^{25,26} Because the majority of capital costs are largely fixed, even small changes in conversion efficiency can materially affect a plant's levelized cost of electricity (LCOE).

MORE THAN TURBINES

The turbine-generator package may be the heart of a geothermal power plant, but significant auxiliary systems are necessary to operate the turbine, handle

Next-generation geothermal pushes operation temperatures above 200°C, opening up new systemwide innovations to maximize performance.

produced fluids, synchronize with the power grid, and maintain performance as reservoir temperatures vary over time. Next-generation geothermal pushes operation temperatures above 200°C, opening up new systemwide innovations to maximize performance.

The turbines used within ORCs are built around two main aerodynamic philosophies: axial-flow and radial-flow turbine designs (**Figure 5**). Axial-flow turbines, which are similar in concept to steam or gas turbines, extract energy through rows of rotating blades along the shaft axis. They perform best at high mass-flow rates and larger scales. Radial-inflow turbines expand vapor that enters the impeller radially inward before redirecting it to exit axially, offering higher pressure ratios and compact form factors ideal for units below roughly 10 MW. For mid- to large-scale systems, axial machines typically deliver superior efficiency, scalability, and manufacturability; radial designs remain competitive for modular or lower-temperature applications. In ORC systems, some equipment manufacturers employ fundamentally different radial-outflow turbines, which combine the compact form factor of a radial turbine design with the high volume flow and high-capacity capabilities of an axial turbine (**Figure 6**).

AXIAL VS. RADIAL TURBINE COMPARISON

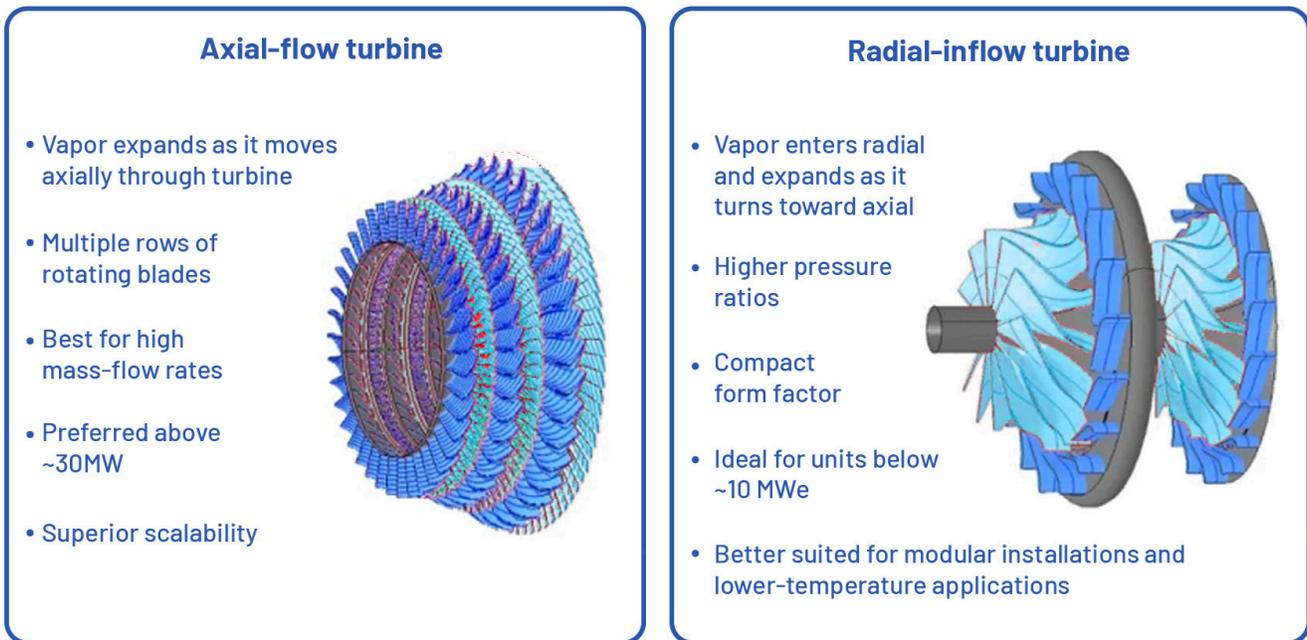


Figure 5: Turbine designs generated in AxSTREAM. Source: SoftInWay. (2023, November 30). [Axial or radial? Selecting the ideal turbomachinery configuration considering rotor dynamic constraints.](#)

Modern ORC turbine capacities have grown from early modules of 15 MWe or 30 MWe to recent orders approaching 50 MWe to 60 MWe per turbine,²⁷ including installations with source temperatures as high as 400°C.²⁸ The primary building block of such a plant is the **turbine-generator train**—a complete package that includes expanders, a gearbox, couplings, a generator, and auxiliaries. Multiple trains can be operated in parallel to achieve the desired output. In large systems, a single train often includes two turbine packages coupled to one generator. Splitting the mass flow across two turbine shafts keeps wheel diameters and tip speeds within mechanical limits and improves aerodynamic efficiency while maintaining a single electrical interface. Using fewer higher-capacity trains reduces complexity for balance-of-plant and maintenance planning but concentrates mechanical and electrical risk into fewer machines—a trade-off mitigated through redundancy management.

Ultimately, the design of any ORC system is driven by practical factors such as mass flow, pressure ratio, manufacturability, and supplier design lineage rather than just nameplate power.

RADIAL OUTFLOW TURBINE DIAGRAM

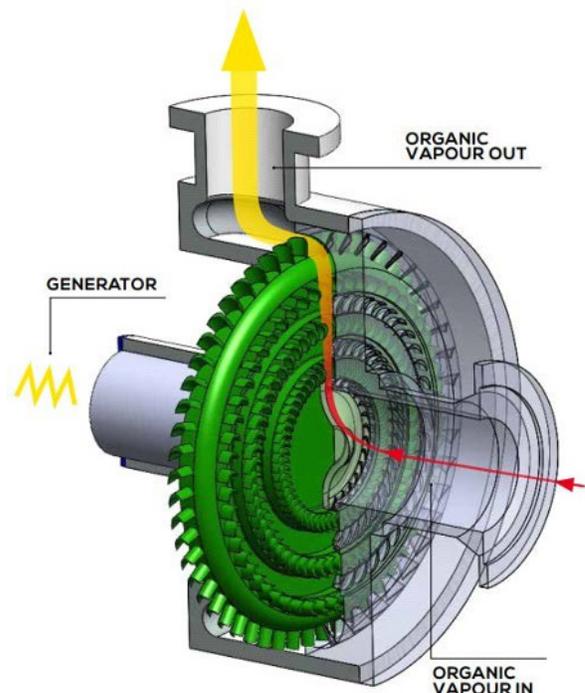


Figure 6: Radial outflow turbine. Source: Exergy, adapted by Franco, A., Vieira, N., & Ponte, C. (2017). [Geothermal developments in Pico Alto, Terceira Island, Portugal.](#) *GRC Transactions*, 41.



An ORC heat exchanger

Chapter 2

Geothermal Demand, Supply Chain Mapping, International Sourcing, and Bottlenecks

ORC GLOBAL SUPPLY LANDSCAPE: WHO BUILDS WHAT—AND WHERE

For ORC plants, most of the schedule and costs live in a few hardware groups: the turboexpander train (rotors and stators or impellers and diffusers, depending on the design; bearings; seals; gearbox and/or coupling; generators), large heat exchangers (evaporator/preheater, condenser, recuperator), and high-volume pumps. Manufacturing of the expander train is concentrated among a small set of OEMs clustered in Israel, Italy, Türkiye, and parts of Europe.²⁹ In the United States, these firms maintain limited production capacity, though existing industrial infrastructure could support meaningful expansion.

To see why logistics and long-lead equipment often set a project's schedule, consider a 10 MWe geothermal ORC unit. The system relies on large heat-exchange pressure vessels, a condenser system, and a factory-assembled turbine-generator block that is typically delivered on one or more skids to simplify installation.

Primary shell-and-tube heat exchangers are commonly about 2 meters in diameter and up to roughly 10 meters in length. Empty shipping weights are typically between 20 tonnes and 50 tonnes per vessel. The turbine-generator block, including base frame and auxiliary systems, often ships as a single oversized skid with an empty weight of between 60 tonnes and 140 tonnes. For higher outputs, OEMs combine multiple trailer-length modules—multiple vaporizer, preheater, and condenser modules—sembled in parallel. These components frequently exceed standard shipping dimensions and weight limits and are shipped as out-of-gauge cargo, often on flat racks or as breakbulk. (A flat rack of 40 feet is generally rated for roughly 38 tonnes in principle, with heavier loads handled on a case-by-case basis.) Delivering this equipment depends on a globally distributed supply chain. Large pressure vessels, foundry-cast and fabricated by specialized pressure-vessel manufacturers, and major ORC components integrated at OEM facilities are made in Italy or Israel before shipment to a geothermal site. As a result, a single 10 MWe ORC train typically involves several

CURRENT PRODUCERS OF LARGE-SCALE GEOTHERMAL ORCS

Original Equipment Manufacturer	Headquarters/Manufacturing Base	Typical Unit Size	Turbine Geometry Type
Ormat	United States/Israel	10 MW–50 MW	Axial
Turboden	Italy (Mitsubishi Heavy Industries)	10 MW–50 MW	Axial
Exergy	Italy/China (TICA Group)	≤20 MW	Radial outflow
Baker Hughes	United States/Italy	5 MW–50 MW	Axial

Table 1: Top producers of large-scale geothermal ORCs today. MW = megawatts; ORC = Organic Rankine Cycle. Source: authors

hundred tonnes of major equipment moving through multiple international and domestic logistics.

In other words, the movement of oversized ORC components is a major contributor to long delivery timelines. Large cast vessels and turbine housings typically move from Asian foundries to European or Israeli assembly facilities and then onward to a project site. Each intercontinental leg—with ocean transit, port handling, customs clearance, and inland transport for breakbulk cargo—can often take one to two months. On the critical path, international shipping can consume roughly three to five months of elapsed time, on the order of one-fifth to one-quarter of the overall 12- to 18-month order-to-delivery cycle. These durations are inherently difficult to compress, but expanding U.S. domestic fabrication capacity would directly reduce schedule risk. Even partial domestic foundry and pressure vessel fabrication capability could eliminate months of transport time and reduce total installed costs by several percentage points.

WHAT THE MARKET DEMANDS IN HARDWARE

Today in the global geothermal market, demand signals, geothermal potential, project pipelines, and manufacturing readiness are beginning to align. Most near-term demand is expected to concentrate in the U.S. given its combination of high technical potential and policy alignment.

Even partial domestic foundry and pressure vessel fabrication capability could eliminate months of transport time and reduce total installed costs by several percentage points.

Since 2020, U.S. geothermal developments (see **Table 2**) include commitments with developers such as Fervo, Sage Geosystems (in partnership with Ormat),³⁰ and XGS Energy.³¹ With their Power Purchase Agreements, these projects are expected to bring 800 MWe, suggesting there is growing market traction—particularly from hyperscale energy buyers like Meta and Google. However, when benchmarked against IEA projections, current commitments fall short of the market opportunity.

According to the IEA, global next-generation geothermal capacity could reach up to 120 GWe by 2035 in a low-cost scenario, with a target cost of approximately \$45 per megawatt-hour.³² Importantly, a significant share of new conventional hydrothermal projects in the United States and Türkiye are using binary cycle systems. This indicates that demand for ORC technology will not solely depend on next-generation geothermal but is already embedded in hydrothermal deployment trends. The market is opening a window of opportunity for an order-of-magnitude increase in both project deployment and hardware manufacturing within the next decade. Given

CAPACITY OF NEXT-GENERATION GEOTHERMAL

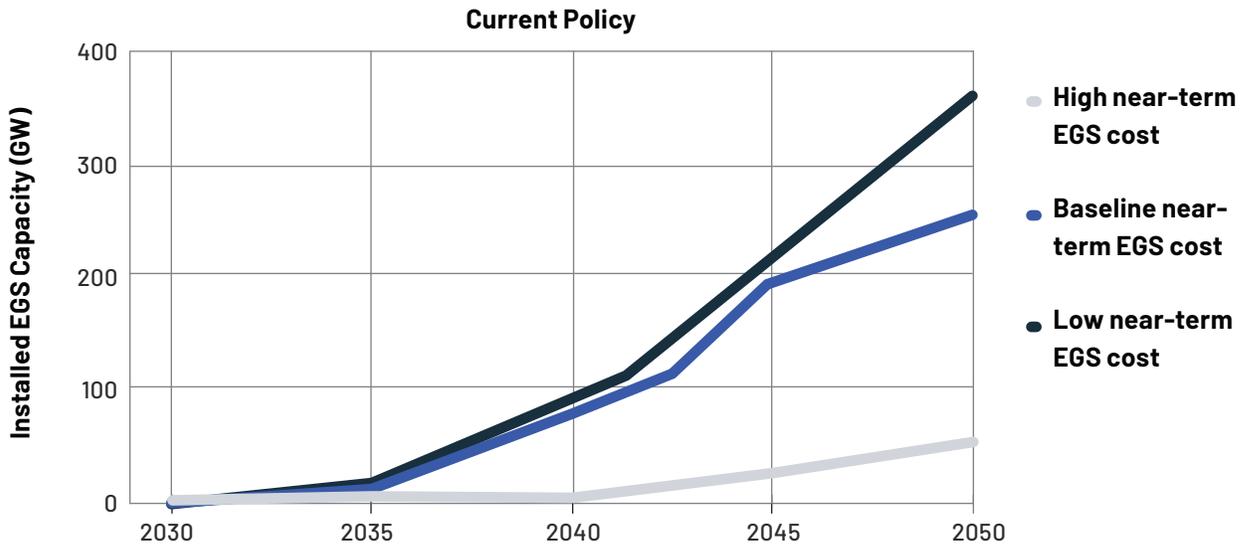


Figure 7: Next-generation capacity assumptions in the U.S. EGS = engineered geothermal system; GW = gigawatts. Source: Adapted from Ricks, W., & Jenkins, J. D. (2025). [Pathways to national-scale adoption of enhanced geothermal power through experience-driven cost reductions](#). *Joule*, 9(7), 101971.

clear and consistent market signals, manufacturing capacity will need to expand rapidly to keep pace with expected demand.

Policy and market structures are starting to respond. For example, California has translated demand for firm, resilient power into new geothermal PPAs, driven in part by hyperscale operators seeking reliable, 24/7 energy sources.³³ At the federal level, the White House Ratepayer Protection Pledge,³⁴ which is discouraging data centers from increasing grid costs for consumers, further strengthens the case for dedicated, behind-the-meter geothermal supply. Together, these signals support a conservative expectation of low double-digit gigawatts of U.S. ORC-class demand by 2035, with substantial upside if cost reductions and procurement momentum continue.

Cost trajectories will play a decisive role in determining how far and how fast the market scales. Recent modeling integrates empirically grounded cost data from commercial pilot programs and the Utah FORGE project into an endogenous experience-curve framework. The results suggest that although initial costs for next-generation geothermal remain high,

early deployment—particularly in the Western United States—can drive significant “learning-by-doing” reductions, especially in wellfield development. These cost declines could unlock nationwide expansion, with next-generation geothermal potentially supplying up to 20% of U.S. electricity by 2050.³⁵ In parallel, demand from data centers could act as a major catalyst. If data center growth follows historical clustering patterns, analysis from Rhodium Group indicates that geothermal could economically meet up to 64% of expected demand growth by the early 2030s under baseline assumptions.³⁶

Taken together, the implication is clear: The technical potential and early market signals are already in place, but realizing this opportunity will require rapid scaling of hardware manufacturing, coordinated deployment, and sustained policy and procurement support.

Policy and market structures are starting to respond. California translated existing orders for firm, resilient resources into new geothermal PPAs.

ORC PROCUREMENT ANNOUNCEMENTS SINCE 2020 (NON-EXHAUSTIVE)

Announcement Date	Project/Site	Country	Total Capacity (MW)	Original Equipment Manufacturer	Buyer/Developer
October-25	Cape Station Phase II	United States	180	Turboden	Fervo Energy
September-25	Cape Station Phase II	United States	300	Baker Hughes	Fervo Energy
June-25	Undisclosed	United States	150	Undisclosed	Meta
May-25	Ribeira Grande Revamp	Portugal	5.3	EXERGY	EDA Renováveis
March-25	Berlin (LaGeo)	El Salvador	7	Turboden	LaGeo
November-24	Maras JES-3 & JES-4	Türkiye	46	EXERGY	Maren Enerji
August-24	Undisclosed	United States	150	Undisclosed	Meta
July-24	Palayan Bayan Binary (BacMan)	Philippines	29	Turboden	Energy Development Corp. (EDC)
July-24	Olkaria Wellhead ORC (8 units)	Kenya	30	EXERGY	RentCo Africa
April-24	Cape Station Phase I	United States	90	Turboden	Fervo Energy
February-24	Minami-Kayabe Geothermal	Japan	6.5	(undisclosed)	ORIX / Minami-Kayabe Geothermal
January-24	Emirler 1 JES Unit 2	Türkiye	8	EXERGY	Emirler Enerji
June-23	HEZ Morali JES-1	Türkiye	24	EXERGY	HEZ Enerji
May-23	North Valley	United States	25	Ormat	Ormat
January-23	Tiwi Binary Plant	Philippines	17	Ormat	AboitizPower
July-22	Casa Diablo IV (CD4)	United States	30	Ormat	Ormat
August-21	San Jacinto-Tizate Binary	Nicaragua	10	Ormat	Polaris Infrastructure
June-21	Salak Binary (Brine Heat Recovery)	Indonesia	14	Ormat	Star Energy Geothermal Salak
May-22	Geretsried (Eavor-Loop) ORC	Germany	8.2	Turboden	Eavor Erdwärme Geretsried
November-20	Greeneco / RSC / Kiper (3 plants)	Türkiye	48	EXERGY	Greeneco

Table 2: Non-exhaustive list of Organic Rankine Cycle (ORC) procurement announcements since 2020. Source: authors.

U.S. PROCUREMENT-PROCESS BOTTLENECKS

Choke points in the geothermal ORC production pipeline stem from a concentration of expertise in a small number of manufacturing shops, along with a limited U.S. talent base for first-article ORC work at modern unit sizes.

Recent project timelines of 12 months to 18 months remain the financeable assumption for a modern ORC train. Standardized designs and pre-positioned (that is, inventory on hand for faster manufacturing) long-lead items can

reduce delivery time. Schedules still hinge on heat exchanger and vessel fabrication and quality assurance throughput, but utility orders help maintain production rhythm and reduce delays. Emerging mezzanine financing structures positioned between equity and senior debt also help shorten timelines by enabling developers to commit to ORC turbine orders earlier in the project timeline, before full financial close. This approach secures manufacturing slots, shortens procurement cycles, and provides OEMs with the confidence needed to initiate fabrication ahead of construction, effectively turning financing flexibility into schedule certainty.

FACTORY INTEGRATION AND DOMESTIC MANUFACTURING PATHWAYS

From a factory standpoint, an axial ORC turboexpander follows similar production choreography as a gas or steam turbine: forging and casting, rough and finish machining, blade fabrication and coating, subassembly, overspeed and balance testing, casing closure, and a full string test with generator and auxiliaries. The required metrology, documentation standards, and workforce skills are in the same class of industrial capability.

Because of this overlap, co-locating an ORC production line within an existing gas turbine manufacturing campus offers substantial advantages over a greenfield build. The approach leverages existing infrastructure, reduces startup time, lowers capital expenditures, and improves bankability through reliance on established quality assurance systems already recognized by lenders and insurers. It should be noted, however, that gas turbine delivery times have slowed dramatically, from historical 12-month delivery schedules to current timelines ranging from three years to five years. This increase has primarily been driven by surging demand for behind-the-meter generation serving data center deployments, and it may, without a market shaping intervention, create an additional burden to product line expansion in the short term.

By leaning into this co-location path, GE Vernova represents a particularly strong domestic platform for a multiproduction strategy. Its U.S. turbine campuses already carry out heavy machining, coating, and overspeed programs. These facilities have nearly all of the core capabilities required for ORC production, so expanding this footprint would require only incremental changes. This approach would shorten qualification timelines, reduce first-article risk (the cost and uncertainty of producing and qualifying the first manufactured unit), and enable rapid scale-up of domestic ORC manufacturing capacity within an existing, bankable framework.³⁷

Baker Hughes recently entered the ORC market with packaged geothermal solutions, drawing on its liquefied natural gas (LNG) turboexpander and steam turbine expertise. Although it is headquartered in the United States, Baker Hughes currently has its

ORC manufacturing base in Italy, making it a domestic OEM with an established European production line. With sufficient commercial pull and policy support, Baker Hughes could credibly localize assembly and test operations in the United States while continuing to source select heavy components internationally during a transition period.³⁸

Beyond geothermal-specialist OEMs, additional supply-chain capacity can come from large industrial players that have already productized ORC solutions in adjacent markets. These entrants can help accelerate geothermal scale in the United States because they expand the pool of bankable counterparties; reinforce standardization; and create additional partnership, licensing, and integration pathways.

Siemens Energy is an example of an adjacent integrator that has incorporated ORC technology into a standardized offering. The company recently developed a scaled ORC capability by leveraging the same industrial turbine design, manufacturing, and service infrastructure that it uses across its steam turbine portfolio. Siemens' ORC offerings span small modular units through midscale frames and extend to large axial ORC turbines in the range of roughly 15 MWe to 20 MWe and up to approximately 55 MWe to 60 MWe depending on boundary conditions. The company positions its ORC turbines as adaptations of proven steam turbine architectures.³⁹

Atlas Copco, via its Gas and Process division, is primarily a supplier of rotating equipment. The company has delivered radial inflow expanders for binary ORC and geothermal applications since the early 1980s and has expanded ORC capacity across geothermal and industrial energy-recovery projects. For geothermal supply chains, Atlas Copco's relevance lies in providing standardized expander platforms with established manufacturing and service infrastructure, which can support modular ORC architectures and reduce dependence on a small number of geothermal-focused OEMs.⁴⁰

In the near term, however, capacity challenges will persist among these OEMs and equipment suppliers. Notably, legacy oil- and gas-supporting product lines are booming with the surge in data center-driven power

The market gap also leaves room for startups willing to move at breakneck pace to get on the board.

demand, the development of LNG export facilities, and the steady growth in demand for aviation gas turbines.^{41,42} At the end of 2025, GE Vernova reported an estimated gas turbine backlog of approximately 80 GWe between current orders and reservation agreements.⁴³ Siemens Energy reported 14 GWe in gas turbine orders coming into the United States (through June 2025), with 65% of those orders going to data centers.⁴⁴

In response to these dramatic demand increases, many of these companies are committing substantial capital to expanding manufacturing. GE Vernova announced a \$41 million investment to expand its facility in Schenectady, New York, on the heels of more than \$130 million invested since 2023, and Mitsubishi Power has announced its intentions to double its global turbine manufacturing capacity over the next two years.⁴⁵ As gas turbine backlogs ease, this could be an opportune time to leverage these facility expansions to support ORC development.

Outside of the gas turbine market, OEMs that supply compressors and pumps are also seeing a significant uptick in orders to support the LNG market worldwide. LNG exporters in the United States have announced intentions to double capacity within the next five years; expansion projects are on track to supply 28.7 billion cubic feet per day (Bcf/d) by 2029,⁴⁶ and more than 40 countries have plans to build or expand LNG terminals in the coming years.⁴⁷ OEMs supporting these legacy oil and gas markets have noted that for every LNG pump sold, about 10 natural gas compressors are required to supply the natural gas to the LNG facility via pipeline and support processes within the plant. In the short term, this growth in LNG exports is also expected to affect the availability and lead time of compressors, pumps, and other products that will be required for geothermal surface plants.

MODULARITY OPTIONS FOR ORCS: WHY STANDARDIZED POWER BLOCKS MATTER

While large, semicustom ORC plants remain the dominant architecture for commercial geothermal today, modularity is an increasingly important lever for both schedule compression and supply-chain resilience. In practice, “modular ORC” means a number of things: from pre-engineered skids (turbine-generator plus auxiliaries) through highly standardized packages and, at the extreme, containerized power blocks that arrive largely assembled and factory-tested.

From a supply-chain standpoint, modularity creates three concrete advantages:

1. It shifts value from site construction to factory repeatability, which supports batch manufacturing, pre-positioned spares, and shorter commissioning cycles;
2. It enables staged deployment, so developers can bring early wells online with an initial set of modules and add capacity in parallel with drilling. Staging can improve project net present value and reduce single-point-of-failure risk; and
3. It broadens the set of manufacturable component suppliers so that standardized subassemblies (skids, coolers, pumps, control panels, lube-oil systems, and the like) can be built by a wider set of U.S. shops, diversifying the vendor base and reducing exposure to any constraints at any single OEM factory.

This market gap also leaves room for startups willing to move at breakneck pace to get on the board. A new OEM within the ORC landscape, Critical Energy Systems, is explicitly designing its business around this modularity thesis. The company focuses on factory-made ORC units that fit within standardized shipping containers.⁴⁸ This strategy aims to shift construction hours and commission risk out of the field and into a controlled factory setting while also keeping logistics standardized.



A modular ORC system

Chapter 3

Ecosystem Dynamics, Policy Levers, and International Trade for the United States

THE DEVELOPER PREDICAMENT

As mentioned, for geothermal project developers, the current landscape for OEMs and turbine supply presents significant structural challenges. While demand for baseload power is increasing, the global supply base for ORC systems remains concentrated among a few established manufacturers, primarily Ormat Technologies, Turboden, Exergy, and others. Limited manufacturer diversity can make it difficult for developers to secure timely delivery. Some issues are manageable with sufficient coordination, capital reinvestment, and policy support. In general, the issues are a drag on deployment, rather than a fundamental barrier.

The more immediate problem is with coordination and information failures created by a thin supply base—and not yet corrected by private markets. Developers cannot reliably signal aggregate demand for noncommodity turbines because each project is bespoke and low volume, so OEMs don't invest much in new manufacturing

capacity. At the same time, turbine qualification and endurance testing are expensive. They often require multimillion-dollar facilities and months of operation at specialized laboratories—costs that exceed what a single developer can bear. **These dynamics generate a collective-action trap: Every project depends on a reliable turbine market, yet no single buyer can justify funding its expansion.**

Recent litigation between geothermal developers and turbine OEMs underscores how concentrated and competitive the supply chain can be.⁴⁹ Patent assertions and exclusive supply arrangements can be used to not only protect innovation but also control access to essential equipment. In such a market, the dominant OEMs' incentives diverge from the public goal of expanding resilient, dispatchable generation. **If left unaddressed, these distortions threaten to create bottlenecks around deployment of geothermal, and advanced power cycles, at precisely the moment when they are needed to diversify the U.S. energy mix.**

When considering increased domestic supply chains and domestic manufacturing for ORC components, the natural argument is that costs will grow. However, the United States continues to on-shore upstream industrial inputs and raw material supply chains, as seen when Nippon Steel announced its intention to (roughly) double its steel production capacity in the United States over the next five years.⁵⁰ This expansion would improve domestic availability of heavy plate, forgings, and casting-grade steel critical to ORC equipment such as pressure vessels, heat-exchanger shells, turbine casings, and shafts. ORC production would get improved access to schedule-critical, specification-compliant material manufactured within U.S. quality and certification frameworks, reducing reliance on long-lead imported components.

Despite the current supply constraints and market concentration, several targeted federal actions could accelerate development of the geothermal ORC manufacturing base.

In addition, NLR modeling suggests that the cost impact of U.S.-based ORC turbine manufacturing will likely be driven by standardization and production volume more than by labor rates. For a 5 MWe ORC turboexpander, for example, NLR estimates a minimum sustainable price of about \$216 per kilowatt (kW) for a custom single unit, falling to about \$66 per kW at five units per year and about \$30 per kW at 50 units per year. This implies that a domestic supply chain can be cost competitive if it supports repeatable designs and scale.⁵¹

In terms of what cost increase is acceptable, the upper bound is set by the incremental value of Internal Revenue Service (IRS) incentives tied to domestic content. IRS Notice 2023-38 describes a domestic content bonus that generally increases the Section 48 investment tax credit by 10 percentage points when requirements are met, or it increases premium tax credit value by 10 percent. This incentive can support a meaningful equipment premium if U.S.-based manufacturing is what enables a project to qualify.⁵²



An ORC turbine & generator

OPTIONS FOR ECOSYSTEM REPAIR

Despite the current supply constraints and market concentration, several targeted federal actions could accelerate development of the geothermal ORC manufacturing base. The following interventions are practical levers that the Department of Commerce, the Department of Energy, and interagency partners could deploy to rebuild industrial capability, de-risk supply chains, and catalyze new entrants in the turbomachinery ecosystem:

- **Make trade deal investments in the turbine supply chain:** Achieve U.S. turbine manufacturing economies of scale through one or more U.S. Investment Accelerator structured investment deals that standardize a series of repeatable designs at varying MW-level thresholds with integrated multiproject testing programs. (See more about the landscape of allied partner trade opportunities in “Creating Allied Manufacturing Corridors.”)
- **Support onshore manufacturing via retooling grants:** Support the reconfiguration and/or expansion of gas turbine, steam turbine, or compressor facilities to produce ORCs, enabling manufacturers to meet emerging customer demand for power equipment.
- **Work with the Department of Energy’s Title 17 Loan Programs Office:** Channel turbine and heat-exchanger manufacturing lines through the Energy Infrastructure Reinvestment (EIR) Program to finance factory capital expenditures, tooling, and supplier scale-up.
- **Replicate the Defense Production Act heat pump model:** Where statutory criteria are met, deploy targeted grants or other transaction authority agreements to establish or expand ORC turbomachinery and critical heat-exchange component lines.

The U.S. turbine and heat-exchanger supply chain is an underappreciated trade opportunity. Rather than relying on insecure supply chains for critical energy hardware, the U.S. can build secure, allied manufacturing corridors for ORC and related systems.

- **Standardize demand signals:** Issue coordinated Department of Energy purchase orders or procurement frameworks for ORC components to create predictable demand visibility.
- **Launch multiyear framework procurements (indefinite delivery/indefinite quantity [IDIQ]):** Through the Hydrocarbons and Geothermal Energy Office and the National Energy Technology Laboratory, ARPA-E, and federal users, aggregate multiyear, multi-agency orders for large heat exchangers, recuperators, ORC expanders, electrical transformers, and grid interconnect equipment to guarantee on-time equipment pipelines for high-priority energy infrastructure projects.
- **Accelerate codes and standards:** Convene the American Society of Mechanical Engineers (ASME) and national labs to finalize test codes and acceptance criteria for CO₂-based and ORC turbomachinery and heat exchangers, adapting existing standards to minimize bespoke, project-by-project validation and testing.
- **Publish open-reference design packages:** Fund and release modular, nonproprietary reference packages detailing process conditions, shaft speeds, bearing and seal envelopes, and auxiliary systems for modular ORCs.

CREATING ALLIED MANUFACTURING CORRIDORS

The U.S. turbine and heat-exchanger supply chain is an underappreciated trade opportunity. Rather than relying on insecure supply chains for critical energy hardware, the U.S. can build secure, allied manufacturing corridors for ORC and related systems. A pragmatic trade policy should emphasize co-production with trusted partners, anchored by U.S. design, testing, and final assembly. **In addition to the Department of Commerce U.S. Investment Accelerator, agencies such as the Export-Import Bank of the United States (EXIM), the U.S. International Development Finance Corporation (DFC), and the Department of Commerce’s International Trade Administration can provide credit, insurance, and export support for U.S. turbine projects that source components from vetted allies under reciprocal market-access rules.** This approach would support U.S. jobs, exports, and long-term energy security, as well as

strengthen the domestic industrial base, reduce project and logistics costs, and expand U.S. competitiveness in resilient and dispatchable power equipment.

India: Precision Components and Forgings

India already plays a pivotal role in precision castings, rotors, and high-temperature alloy forgings, all of which are essential for turbine and heat-exchanger manufacturing. Under existing plans,⁵³ India and the United States could establish a bilateral manufacturing corridor with EXIM and DFC support for joint ventures to supply components to U.S. assembly plants. India's skilled labor, cost competitiveness, and aligned geopolitical interests make it an ideal partner for intermediate production. This arrangement could shorten supply chains; reduce dependence on China; and sustain U.S. jobs in testing, integration, and export.

South Korea: High-Pressure Turbomachinery and Printed-Circuit Heat Exchangers

South Korea's advanced turbine and aerospace manufacturing base, chaired by global leaders such as the Doosan Group and the Hanwha Group, has world-class capabilities in high-pressure turbomachinery, precision seals, and printed-circuit heat exchangers. Building on the new U.S.-Korea trade framework,⁵⁴ a manufacturing partnership could extend beyond semiconductors to encompass energy-conversion and propulsion equipment, positioning allied industries at the core of resilient supply chains.

Japan: Reliability and Standards Leadership

Japan remains a global benchmark for turbine efficiency, precision bearings, and reliability engineering. Firms such as the IHI Corporation, Kawasaki Heavy Industries, and Mitsubishi Heavy Industries (which owns Turboden) are already advancing ORC technologies. The recent trade deal between the U.S. and Japan laid the groundwork for significant investment from Japan's corporations, supplying the market with a broad range of turbines on the near-horizon.

Germany and Italy: ORC and Controls Expertise

Germany and Italy form Europe's hub of turbine innovation, home to Siemens Energy, Schaeffler, Turboden, Nuovo Pignone (Baker Hughes), and Exergy. A transatlantic industrial standards pact could align ASME and EN certifications, allowing U.S. firms to export turnkey systems globally. EXIM-backed demonstration projects under the EU-US Trade and Technology Council could facilitate co-development while ensuring that publicly funded intellectual property remains accessible to U.S. firms. Italy's ORC specialization and Germany's controls and materials capabilities would help close key supply-chain gaps without displacing domestic manufacturing.

Central Europe: Surge and Overflow Capacity

Legacy turbine and compressor factories in the Czech Republic and Poland remain underutilized yet technically capable. Through the Three Seas Initiative Investment Fund and DFC participation, the United States could help expand these NATO-aligned facilities to handle overflow production and surge demand. This expansion would create a secure secondary source of components within the Atlantic alliance, strengthening allied economies and reducing exposure to China.



Plate heat exchangers and manifold system

Chapter 4

Unlocking Capital for Emerging Tech

FINANCING GEOTHERMAL PROJECTS

Financing next-generation geothermal requires navigating a complex landscape that bridges high-risk, early-stage exploration with the need for stable, long-term returns required by infrastructure investors. Because next-generation geothermal projects are capital-intensive and face unique subsurface risks, their financing relies on a “stack” of capital that includes government risk mitigation, strategic corporate partnerships, tax incentives, and long-term contracts. (See **Table 3.**)

PURCHASING OF TOPSIDE COMPONENTS

As **Table 4** shows, heat-exchange equipment and cooling systems represent the majority of surface plant capital expenditures. At commercial scale (50 MWe installations), surface plant costs typically range from \$80 million to \$120 million,⁵⁵ which, as mentioned

Geothermal developers could deploy modular surface plant capacity as soon as they achieve commercial flow rates, enabling revenue generation during the extended appraisal period while reservoir performance is validated and additional wells are drilled.

earlier, could be about 40% to 50% of the total capital expenditures for a geothermal project when combined with subsurface drilling and completion costs.

CAPITAL FORMATION AND MODULAR DEPLOYMENT STRATEGIES

In one scenario, geothermal developers could deploy modular surface plant capacity as soon as they achieve commercial flow rates, enabling revenue generation during the extended appraisal period while reservoir performance is validated and additional wells are drilled.

OVERVIEW OF THE CAPITAL STACK FOR NEXT-GENERATION GEOTHERMAL DEVELOPMENT

Project Stage	Primary Funding Sources	Key Mechanism
Exploration/Pilot	Government grants, corporate equity	De-risking technology and resource confirmation
Drilling/Construction	Tax equity, strategic partnerships, high-cost debt	Investment tax credits (30% reduction), joint ventures to manage high capital expenditures
Operation	Project finance	Long-term Power Purchase Agreements provide the stable cash flow that banks require to lend

Table 3: Capital stack for next-generation development. Source: Adapted from Lines, T., Merino-Garcia, D. Kleinhaus, K., & Beard, J. (2026). *Minding the gap: Geothermal financing at oil and gas scale*. Project InnerSpace.

This approach would substantially improve project risk profiles by demonstrating both technical viability and cash flow generation to prospective lenders and equity investors. It could also accelerate access to lower-cost project financing for full-scale development. Modular units in the range of 2 MWe to 4 MWe could be deployed iteratively as reservoir extent is proven, with developers adding capacity incrementally rather than committing to multi-hundred-megawatt installations based on limited operational data.

This approach, however, could run counter to the benefits of economies of scale. Large single-train installations reduce balance-of-plant costs per megawatt, and they simplify operations and maintenance, unlike deploying modular surface capacity.

This trade-off becomes particularly acute given long equipment lead times: Committing to a large integrated

facility requires confidence in long-term reservoir performance based on limited operational history. The optimal configuration depends heavily on resource certainty, financing structure, and offtake agreement terms. Unfortunately the industry currently lacks the equipment supply flexibility to fully exploit either strategy.

OEM BUSINESS MODELS AND BARRIERS TO MARKET ENTRY

Existing OEM market dynamics muddy the waters for potential new market entrants. Several established manufacturers offer project equity in exchange for equipment supply agreements, effectively providing early-stage development capital while creating captive markets for their products. Under these arrangements, OEMs accept compressed margins on hardware sales, in some cases approaching cost, while capturing returns through long-term EPC contracts

REPRESENTATIVE COSTS FOR PARTS OF AN ORC SYSTEM

Component	Typical Share of Total EPC Cost (Order-of-Magnitude)	Description
Turbine-generator package	~30%-40%	Complete rotating equipment train, including turbine, gearbox, generator, and couplings
Heat-exchange equipment	~45%-60%	Primary heat exchanger, recuperator, cooling systems, circulator pumps
Electrical and control systems	~5%-10%	Instrumentation, controls, power equipment
Balance of plant	~15%-25%	Piping, valves, structures, shipping, structural steel

Table 4: Representative costs for various parts of an ORC system. Source: internal analysis of information from industry vendors.

and operations and maintenance agreements. This integration strategy provides developers with access to capital and operational expertise but concentrates margin capture in downstream services rather than equipment manufacturing.

For prospective new entrants focused on turbomachinery or heat-exchanger production, this business model presents barriers because established players can underprice equipment to protect high-margin service revenue. Developers accustomed to integrated financing and technical support packages may also resist this unbundled equipment procurement approach, even if unit costs are lower.

The complexities surrounding next-generation geothermal technology development and funding pathways, coupled with the escalation in both support and demand for gas turbines and the build-out of LNG infrastructure, put geothermal power projects in a tricky risk category—one that investors often pass over. For a deep-dive analysis of the financial and capital pain points, see *Minding the Gap: Geothermal Financing at Oil and Gas Scale*.⁵⁶

Bankability Considerations

It is hard to underwrite new technology purchases out of a line of credit and justify them as a valid use of capital. Right now, subsurface geothermal development carries oil and gas drilling risk, while revenues depend on baseload power asset economics. This profile complicates equipment procurement decisions, as unproven surface plant technologies require up-front capital commitments that developers struggle to justify against construction lending agreements.

Historically, federal policy tools have stepped in to bridge the financing gap for new renewable technologies on their path to commercial acceptance. These financing and tax credit incentives, however, primarily support the deployment of established technologies rather than addressing the “valley of death” between prototype demonstration and commercial bankability and can change quickly depending on an administration’s priorities.

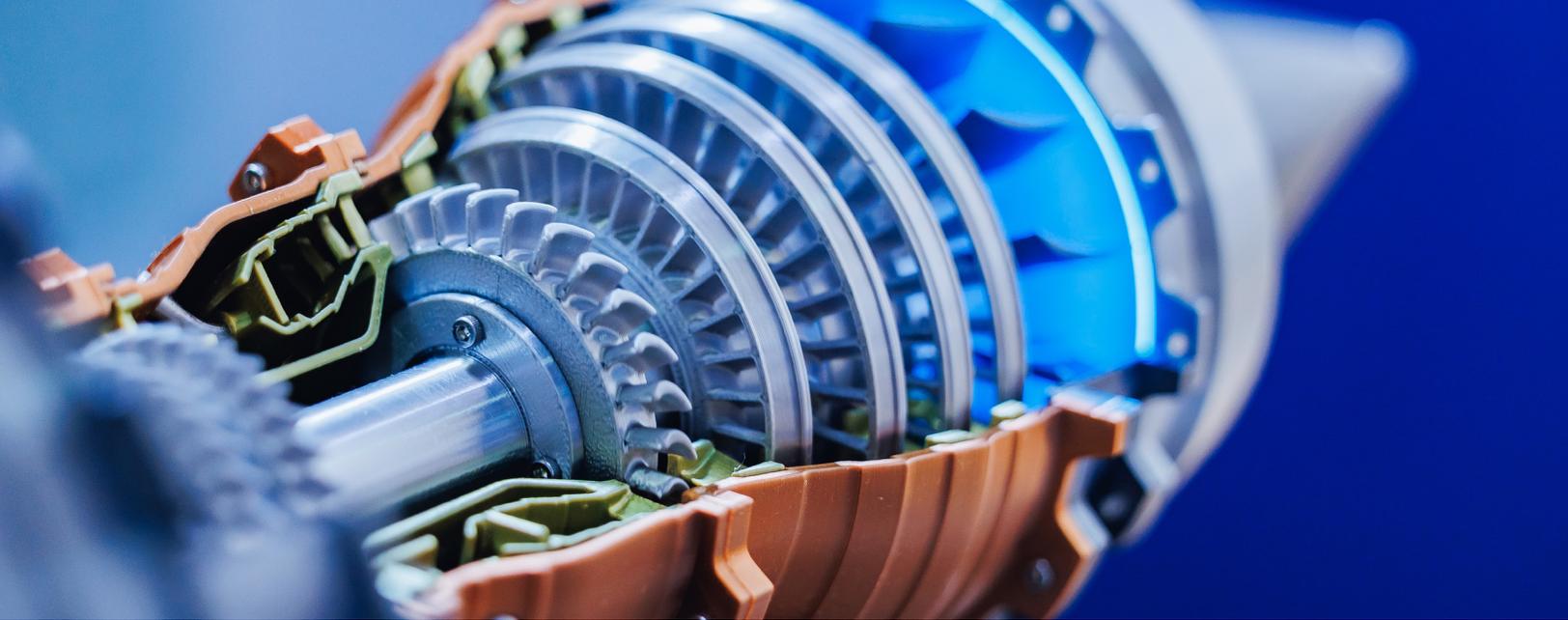
The urgency of the current power market may shift historical precedent and create pressure to compress technology validation cycles. The tension between

traditional bankability requirements and today’s market presents potential opportunities for surface plant innovation. Equipment manufacturers that offer performance guarantees or leasing models, manufacturers with established operational track records in adjacent applications, and hybrid financing structures that blend risk insurance with manufacturer warranties may enable faster commercial adoption. Additionally, policy mechanisms could accelerate market entry for novel designs offering superior performance or cost advantages.

Data center-driven load growth changes the risk calculus around validation timelines. Hyperscalers and large cloud operators are facing constraints on not only energy cost but also calendar time, with multiyear grid interconnection queues and turbine delivery backlogs that are increasingly incompatible with their deployment schedules.

Unlike traditional utility procurement, data center buyers can tolerate narrower operating histories if risks are bound through redundancy, staged capacity additions, or contracts tied to availability rather than lifetime efficiency. In practice, this favors surface plant architectures that can be deployed incrementally, validated in parallel with operation, and expanded rapidly with confidence.

When paired with government-backed credit support or insurance wrappers, hyperscaler demand can effectively act as a bridge market, pulling Technology Readiness Levels (TRL) 6–7 surface technologies into commercial operation earlier than would be possible under conventional utility-led bankability frameworks—while still preserving a credible path to full project finance.⁵⁷



An additive manufactured jet engine turbine. High-throughput manufacturing techniques like 3D printing hold great promise to speed the production of turbomachinery components.

Chapter 5

Moonshots and Prototypes of the Future

In this section, we outline the top technological advancements in geothermal turbomachinery that are poised to improve efficiencies, reduce costs, and shorten the supply chain.

THE CO₂ BRAYTON OPTION: WHY COMPACTNESS MIGHT WIN

As drilling costs decline and deeper, hotter reservoirs become commercially viable, surface plant technology must evolve to convert the heat efficiently.

ORC systems remain the default choice in current next-generation geothermal applications: They are mature and financeable, as well as tolerant of the brine chemistry, scaling, and flow variability that show up in commercial projects. The main innovation frontier is not a new working fluid for ORCs but alternative power blocks using carbon dioxide (CO₂) as the working fluid, particularly in supercritical and trans-critical configurations.

There are two relevant CO₂ cycle families for geothermal. Supercritical CO₂ (sCO₂) Brayton cycles operate entirely above the CO₂ critical point; compression, heating, expansion, and cooling all take place in the supercritical region. Transcritical CO₂ (tCO₂) cycles compress above the critical point but reject heat below it, resembling a Rankine-style loop with a liquid-like compression step. In both cases, the hardware looks similar: a compressor, primary heater, turbine or expander, recuperator, and cooler assembled into a compact “CO₂ block.”

The difference between these CO₂ blocks and ORCs is less about the flow diagram and more about operating conditions and physical scale. ORCs typically operate at moderate pressures and use relatively large-diameter turbines running at synchronous speeds. CO₂ systems operate at much higher pressures and shaft speeds, often above 20,000 rpm, so for the same net power, they can be built much smaller. A smaller power block means less steel, fewer large castings and forgings, smaller foundations, and greatly simplified shipping and lifting.

SUPERCRITICAL CO₂ POWER CYCLE SYSTEMS DIAGRAM

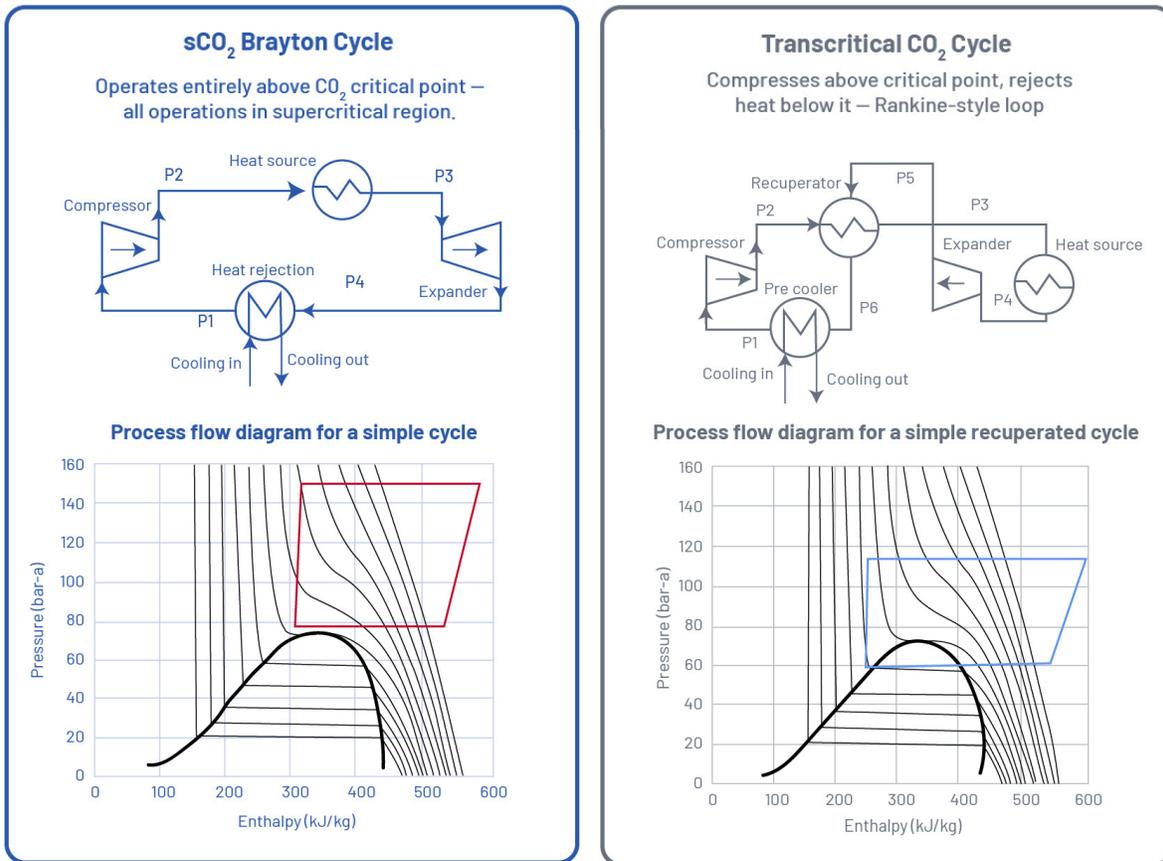


Figure 8: Schematic and pressure-enthalpy diagram for two example power cycles, utilizing carbon dioxide as the closed-system working fluid. Source: authors.

This matters when developers are trying to deploy dozens or hundreds of units into constrained supply chains.

In typical geothermal temperature ranges, well-tuned ORCs generally still deliver higher net thermal efficiency than first-generation CO₂ systems. The argument in favor of sCO₂ and tCO₂ is not about their thermodynamic superiority but about hardware economics and deployment speed. If a CO₂ block can be standardized, replicated in volume, and delivered quickly, its smaller footprint and simpler logistics may reduce installed cost and shorten time to power. In project terms, a modest efficiency penalty may be acceptable if the net present value is higher because the plant would be cheaper to build, faster to come online, and easier to expand.

More data would be required to analyze this further, but three technical and manufacturing factors largely determine whether that trade-off is achievable:

- First, recuperators and coolers dominate cost and lead time. CO₂ recuperators, often compact printed-circuit or similar designs, must combine extremely fine flow passages with robust walls and joints to withstand high pressures while delivering high effectiveness; existing stainless-steel diffusion bonded heat exchanger technologies are well suited to meet the needs, but cost and procurement lead times must be improved. Their geothermal variants must manage both the CO₂ side and a brine-side heat-exchange surface that may see fouling or corrosion. These components must be manufacturable at scale, not just as one-off prototypes.
- Second, high-pressure durability requires proven materials, seals, and quality assurance. Pressure-boundary alloys, welds, and joints need a clear path from coupon testing to full-life components, with fatigue and creep behavior characterized under realistic load profiles. Shaft end seals (often dry gas

A reasonable near-term hypothesis is that although CO₂ power cycles may trail modern ORC systems in thermal conversion efficiency, their significantly smaller form factor at equivalent nameplate capacity—combined with standardized packages and supply chains—can deliver lower installed capital expenditures and shorter lead times, making them economically competitive.

seals with small operating clearances) are critical for maintaining the high operating pressures inside these turbomachines. A well-defined seal gas supply system and plant controls code will be required to ensure longevity and proper operation of these dry gas seals; the tight operating clearances mean leakage rates are small but also that these seals are susceptible to failure in minor upset conditions.

- Third, high-speed turbomachinery requires tight clearances and consistent fabrication of integrally manufactured wheels and shrouds. Rotor-dynamic stability, bearing life, and seal clearances at speed all depend on repeatable machining or printing, reliable metrology, and well-understood assembly procedures.

If these gates are cleared, compact CO₂ power blocks could offset the marginally lower thermal efficiencies with advantages in size, cost, logistics, and deployment speed. A reasonable near-term hypothesis is that although CO₂ power cycles may trail modern ORC systems in thermal conversion efficiency, their significantly smaller form factor at equivalent nameplate capacity—combined with standardized packages and supply chains—can deliver lower installed capital expenditures and shorter lead times, making them economically competitive. Under this framework, ORC remains the default choice for geothermal resources, but CO₂ cycles may become competitive when the technical gates outlined earlier are cleared, with standardized designs that reduce project cost and schedule.

THE ROLE OF ADDITIVE MANUFACTURING

Manufacturing, of course, is just as important as thermodynamics. Compact CO₂ blocks are unusually well aligned with current additive manufacturing

capabilities. Many components that are hardest to fabricate conventionally—because they require complex internal passages or fine features—can be produced effectively via additive manufacturing.

Additive manufacturing offers several practical advantages for CO₂ hardware. It reduces the total mass of sourced and qualified materials, since parts are built near net shape rather than carved out of large forgings or plates. It also allows designers to optimize internal flow paths for performance rather than for tool access. But there's a cost and timeline trade-off, as additive manufactured parts require post-fabrication procedures. Once part designs and qualification procedures are established, critical spares can also be produced on demand, near the point of use, which shrinks outage duration.

Modern ORC systems can also benefit from additive manufacturing in selective areas. Their equipment lists remain dominated by large shell-and-tube heat exchangers, condensers, pressure vessels, and structural steel that primarily require rolled plates, conventional welding, and heavy casting. That said, additive manufacturing might be applied to specialized nozzles, flow distributors, or certain hot-gas-path components in ORC turbines.

By contrast, a CO₂ turbine module is a natural candidate for a domestic, additive-heavy manufacturing, as a much larger fraction of its value can be in additive-compatible components. Within turbine and compressor housings, internal manifolds, lattice-like support structures, and blades can also be printed, sometimes using multiple metals to tailor strength, fatigue life, and thermal conductivity in different regions of the same part. The main exceptions—pressure casings, shafts, bearings, elastomers, and some seal elements—would continue to come from established rotating-equipment supply chains.

In the United States, a fully domestic CO₂ block supply chain is technically and commercially plausible. Additive manufacturing and modular assembly could compress procurement, fabrication, and shipping cycles from months to weeks for repeat builds, after designs are frozen and print parameters qualified. For maintenance and spare parts, compactness further simplifies logistics because critical components can be printed domestically and staged regionally.

MODULAR TURBINE OPTIONS

The third piece of the picture is architectural: modular turbine options. Today's commercial ORC plants are typically engineered as semicustom projects. Turbine-generator trains are sized and tuned for specific brine conditions and site constraints; condensers and heat exchangers are designed for each project; and major components are shipped and assembled on-site with substantial piping, structural, and electrical work.

That project-by-project model works, but it drives long lead times, high engineering overhead per megawatt, and limited repeatability. It also forces developers into large, cumbersome procurement decisions.

In contrast, a modular turbine approach builds plant capacity out of standardized power blocks. Each module is a self-contained package with a standard mechanical and electrical interface. Capacity is added by running multiple modules in parallel instead of designing a single large expander. A multi-megawatt sCO₂ module can be designed to fit within standard shipping container dimensions. Foundations, piping headers, and electrical connections can be standardized so that site work becomes an assembly process rather than a bespoke construction project, lowering EPC cost. Onsite, the work shifts toward setting modules, making a small number of connections, and commissioning using familiar procedures.

For manufacturers, modularization changes the economics. Instead of engineering one-off trains, they can focus on a small family of module sizes and build them in batches. Long-lead components can be produced ahead of firm orders and held in inventory under framework agreements. For developers and operators, modular turbine options offer different types of flexibility. Capacity can be staged, and then a project can start with a subset of modules to serve early loads and add more units as additional wells are drilled or as demand grows. Maintenance becomes modular too. From a financing standpoint, standardized modules with documented performance and reliability data simplify independent engineering review and underwriting.

Conventional ORC technology can, in principle, be modularized in a similar way, but the physical scale

of conventional ORC hardware makes it challenging to achieve full containerization. Large shell-and-tube exchangers, high-volume condensers, and heavy casings mean it is difficult to fit an entire multi-megawatt ORC train into a small number of skids or containers. However, startup innovation, such as that from Critical Energy, is emerging with modular ORC packages sized around 2 MW, which fit into standard shipping containers for deployment capabilities in less than 30 days from the order date. While other smaller modular ORCs exist, larger outputs are viewed as more economical with field-erected equipment, a paradigm that is beginning to change.

In contrast with conventional ORC systems, CO₂ modules start from a smaller form factor. That inherent compactness at larger scales makes it easier to deliver pre-assembled, factory-tested power blocks that arrive on site largely complete. If, over time, these modules can be shown to deliver materially shorter lead times and lower installed cost per kilowatt than custom ORC trains while meeting reliability and lifetime targets, they become a natural candidate for the default binary power block in higher-temperature geothermal projects.

In that sense, the ultimate goal is not a single cycle or novel material. It is the combination of compact turbine-generation blocks, additive manufacturing, and modular turbine architectures that can move geothermal power hardware from bespoke heavy equipment toward standardized, repeatable power blocks.

Advancing CO₂ technology in geothermal turbomachinery will require continued research, modeling, and prototyping, supported by public programs or industry consortia. Early demonstration units will likely have lead times like those of current ORC plants, as design standards and supply chains are still maturing. But over time, as printable subcomponents and modular assemblies are standardized, production timelines can shorten significantly.

By co-developing additive manufacturing supply chains alongside sCO₂ and tCO₂ test programs, the United States could accelerate readiness for both technologies and create a modular, flexible manufacturing base capable of producing compact, high-efficiency power blocks for geothermal, industrial, and defense applications.



Insulated ORC piping system

Chapter 6

Conclusion and Recommendations

The geothermal sector is at an inflection point. Subsurface technology has advanced substantially, driven by cost reductions borrowed from oil and gas drilling, yet surface plant manufacturing has not kept pace. ORC turbines, heat exchangers, and cooling systems remain largely bespoke, sourced from a thin international supplier base, and subject to lead times that routinely stretch 12 months to 18 months. Without deliberate intervention or a firm market signal, surface equipment will become the binding constraint on deployment velocity and project economics, regardless of how far subsurface costs fall.

Closing this gap requires coordinated action across manufacturers, developers, investors, and policymakers, each of whom must move in parallel rather than sequentially. The transition from custom, project-by-project execution to standardized, high-volume manufacturing is not inevitable; it requires the kind of demand certainty, financing innovation, market shaping, and industrial policy that has unlocked scale in other

renewable energy sectors. The tools and industrial assets to accomplish this largely exist within the United States and its allied manufacturing base. The central challenge is not technological readiness but the coordination failures that prevent manufacturers, capital, and policy from moving together.

CURRENT TURBINE SUPPLIERS

Established gas turbine and industrial turbomachinery manufacturers are well positioned to scale ORC production for geothermal by leveraging active turbine campuses, skilled labor, and mature quality systems. Co-locating ORC assembly and testing within existing facilities takes advantage of installed precision machining assets, rotor-dynamics expertise, generator integration capability, and supplier networks while keeping incremental capital requirements relatively low compared with building a manufacturing facility from scratch. Baker Hughes illustrates this path directly: The company entered the geothermal ORC market by adapting

its LNG turboexpander and steam turbine engineering, applying a manufacturing lineage built entirely around gas applications to produce packaged binary-cycle systems for geothermal power generation.

Adding domestic ORC manufacturing capacity can also unlock meaningful policy and tax advantages, which improves the economics of diversification at a time when gas turbine production lines are increasingly under pressure due to rising energy demand.

For existing geothermal turbine OEMs, publishing aggregated performance data, typical lead times, and reference cost ranges (without disclosing proprietary designs) would further reduce friction in project underwriting. This additional layer of transparency could directly address the coordination failures highlighted in this analysis. As geothermal deployment accelerates, competitive advantage for incumbent OEMs will increasingly depend on not only efficiency but also execution certainty, modularity, and the ability to integrate into financing structures that prioritize speed-to-power and scalable replication.

Notably, open-source techno-economic modeling can be limited because of reliance on outdated assumptions and data, which underpin the capital expenditure and efficiency calculations for surface facility economics. The absence of current data in these models can lead to economic projections that are less favorable than what would likely be seen in practice. These projections could also restrict developers' financing options, essentially meaning the OEMs would be hindering themselves, undermining the market potential they aim to capture. Open-sourcing better, up-to-date data that allow for more accurate techno-economic modeling is an easy way to create a positive feedback loop—and break free from the predicaments currently stifling geothermal market growth.

STARTUPS AND NEW COMPANIES

New entrants to turbine and related systems manufacturing are well positioned to target gaps in the existing geothermal surface-plant ecosystem, such as standardized modular subsystems and integration layers that incumbents have little incentive to make into repeatable products under a bespoke EPC-driven

model. Startups that focus on well-defined hardware with repeatable interfaces can create leverage without assuming full plant responsibility or bankability risk prematurely. These companies would likely get the best commercial traction when deployment speed and configuration flexibility matter more than marginal efficiency gains. In situations such as behind-the-meter geothermal that serves data centers, value accrues to suppliers that can deliver predictable schedules, modular expansion pathways, and clear operating envelopes rather than lowest theoretical cost.

Publishing better, up-to-date data that allow for more accurate techno-economic modeling is an easy way to create a positive feedback loop—and break free from the predicaments currently stifling geothermal market growth.

INNOVATORS AND R&D LEADERS

Working with higher reservoir temperatures (200°C–300°C and above) means that a developer can use ORCs as well as supercritical CO₂ turbines, steam, and other advanced cycles. These systems can offer compact form factors and potentially higher thermodynamic efficiency, particularly where surface footprint, logistics, and installation time are binding constraints. The practical value of these systems will be determined more by system-level performance once they are integrated into real geothermal plants than by peak efficiency. Parasitic load management, seal and bearing life, and stable operation across wide ambient temperature ranges remain the first challenges. Research and development efforts should therefore focus on validating supercritical CO₂ turbines or other novel and advanced cycles under the conditions that are expected for next-generation geothermal rather than narrow design-point conditions.

This approach includes documenting performance across ambient temperature swings, part-load operation, and cycling duty, as well as characterizing degradation and maintenance requirements over sustained runtime. Publishing operating-condition-resolved performance data would align with efforts to demonstrate bankability and accelerated validation; it would also enable

developers and financiers to assess realistic trade-offs between compactness, efficiency, availability, and deployment speed as higher-temperature geothermal resources move toward commercial scale.

INVESTORS

Investors should prioritize companies that address the bottlenecks that create the highest costs in the geothermal and advanced power supply chain—particularly where additive manufacturing, modularization, or standardization can compress delivery timelines. The most attractive opportunities are likely to be in enabling layers rather than fully integrated plant offerings. This includes standardized turbogenerator packages, optimized heat exchangers and cooling systems, factory-packaged auxiliaries, predictive maintenance and controls software, and project development tools that reduce engineering and execution risk. As this analysis outlines, these components are frequently on a critical path for deployment and disproportionately influence schedule and cost outcomes.

Capital can do more than fund incremental equipment improvements. Investors are in a position to help shape demand itself. By lining up projects in advance, supporting common technical standards, and committing money early to secure equipment, investors can turn scattered interest into a clear, predictable pipeline of signed orders that manufacturers can rely on. Manufacturers invest in capacity when they see repeatable demand, not when they see isolated pilots. Order certainty, more than marginal efficiency gains, is a clear pathway to unlocking scaled manufacturing.

At the same time, investment plans must account for incumbency advantages around bankability, manufacturing track record, and access to project finance. Displacing established suppliers on hardware alone is unlikely without either matching incumbent financing

capabilities or materially changing risk perception for lenders and offtakers. This places a premium on having superior operational data, clearly defined performance envelopes, and credible availability or warranty structures that can be underwritten. Supporting portfolio company participation in industry data-sharing initiatives, funding independent engineering validation, and underwriting early runtime accumulation can accelerate this transition, aligning private capital with the broader emphasis in this analysis on execution certainty, transparency, and accelerated commercialization.

Durable demand signals reduce manufacturing risk faster than incremental technical gains.

POLICYMAKERS

Federal support for geothermal and advanced power cycles should extend beyond project-level subsidies and include deliberate investment in domestic manufacturing capacity and industrial capability. Targeted Department of Commerce, Department of Energy, and ARPA-E programs can play a catalyzing role by bolstering a steady-state domestic manufacturing supply base, turbomachinery R&D, advanced cycle development, and manufacturing process innovation that takes the risk out of first-of-a-kind *production* rather than only first-of-a-kind projects. Enhanced investment tax credits and premium tax credits tied to domestic content are particularly important in this context, as they create enduring demand certainty that justifies private investment in factories, tooling, workforce training, and supplier qualification. Without this forward visibility, manufacturers rationally underinvest in capacity, perpetuating existing bespoke, low-volume dynamics.

Public policy can reinforce this transition by moving beyond project-by-project subsidies toward deliberate market formation. Advance market commitments, coordinated public procurement, and performance-based prize structures can create durable demand for standardized or novel power blocks. When manufacturers can see credible, multiyear order flow, they are more likely to invest in tooling, workforce expansion, and supplier qualification.

Advance market commitments, coordinated public procurement, and performance-based prize structures can create durable demand for standardized or novel power blocks.

Market shaping is therefore not an abstract concept but a practical industrial strategy tool. Clear performance targets, standardized acceptance criteria, and procurement commitments tied to delivery milestones reduce perceived risk across the supply chain. Policy that generates predictable demand often accelerates capacity build-out more effectively than one-off capital grants.

In parallel, policy should actively support supply-chain resilience for critical components such as forgings, bearings, seals, and heat exchangers during domestic scale-up via agreements with allied manufacturing bases in India, South Korea, Japan, and Europe. These partnerships can shorten lead times and reduce exposure to adversarial suppliers while U.S. capacity is rebuilt. Domestically, Defense Production Act authorities and Title 17 financing can be used to retool or expand existing U.S. turbomachinery facilities for ORC and sCO₂ or tCO₂ production. This would leverage installed industrial assets rather than starting from scratch.

Finally, mandating the publication of anonymized project performance data, equipment specifications, and cost structures—particularly for publicly supported projects—would reinforce the central thesis of this analysis that transparent operational data can accelerate learning, improve bankability, and enable more efficient capital allocation across the sector.

Market shaping converts policy support into predictable order flow.

THE PATH FORWARD

Next-generation geothermal systems offer a credible pathway to gigawatt-scale firm, dispatchable, abundant power that aligns with emerging grid and data center demand. As this analysis has outlined, the principal constraint is a combination of subsurface feasibility and the surface plant supply chain, which remains dominated by custom engineering, thin manufacturing bases, and long lead times. Moving from bespoke surface facilities toward standardized, high-volume manufacturing of turbines, heat exchangers, and auxiliary systems is

therefore central to unlocking scale, compressing schedules, and bending cost curves.

Doing this work requires more than incremental engineering improvement. It requires coordination across capital providers, developers, manufacturers, and policymakers to align incentives around standardized, repeatable hardware platforms.

The technical building blocks already exist to make this transition across the United States and its allied industrial base. The remaining challenge is coordination: firm and clear market signals in high-temperature geothermal, capital deployment, financing structures, and policy tools to spur technology development and innovation so that manufacturers can invest ahead of the curve and developers can procure equipment with confidence.

Moving from bespoke surface facilities toward standardized, high-volume manufacturing of turbines, heat exchangers, and auxiliary systems is central to unlocking scale, compressing schedules, and bending cost curves.

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“Without deliberate intervention or a firm market signal, surface equipment will become the binding constraint on deployment velocity and project economics, regardless of how far subsurface costs fall.”

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