Quadrennial Technology Review 2015

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ENERGY

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Supercritical Carbon Dioxide Brayton Cycle

Chapter 4: Technology Assessments

Introduction

The vast majority of electric power generation for the grid is accomplished by coupling a thermal power cycle to a heat source. The nature and configuration of the thermal power cycle is designed so as to give as efficient power production as is economically attractive. Much of the DOE R&D portfolio is focused on improving the overall efficiency and economics of electric power generation. To that end, there are three primary areas of focus for R&D to improve electric power generation efficiency: (1) increasing the fraction of the energy in the heat source that can be harvested for use in the thermal power cycle; (2) increasing the intrinsic efficiency of the thermal power cycle; and (3) decreasing the parasitic power requirement for the balance of plant (BOP). As will be discussed further below, the first two focus areas cannot be pursued in isolation as they are often antagonistic. For example, recuperative heat exchange within the thermal power cycle can often lead to a higher cycle efficiency but this may be at the expense of decreasing the amount of heat that can be transferred into the cycle and lowering the overall process efficiency.

Most of the thermal power cycles in commercial operation are either air-breathing direct-fired open Brayton cycles (i.e., gas turbines) or indirect-fired closed Rankine cycles which use water as a working fluid (typical in pulverized coal and nuclear power plants). Within each group are a myriad of potential configurations that vary in size and complexity. For any application, the best thermal power cycle will depend on the specific nature of the application and heat source.

In addition to these conventional thermal power cycles, cycles based on other working fluids can be considered. In particular, the Brayton cycle based on supercritical carbon dioxide (sCO_2) as the working fluid is an innovative concept for converting thermal energy to electrical energy.

Numerous studies have shown that these sCO_2 power cycles have the potential to attain significantly higher cycle efficiencies than either a conventional steam Rankine cycle or even the state-of-the-art ultra-supercritical (USC) steam Rankine cycle.[1,2,3] Higher cycle efficiency will automatically lead to lower fuel cost, lower water usage, and in the case of fossil fuel heat sources, lower greenhouse gas (GHG) emissions. Further, the sCO_2 cycles operate at high pressures throughout the cycle, resulting in a working fluid with a high density which may lead to smaller equipment sizes, smaller plant footprint, and therefore lower capital cost. Achieving the full benefits of the sCO_2 cycle will depend on overcoming a number of engineering and materials science challenges that impact both the technical feasibility of the cycle as well as its economic viability.

As will be discussed in greater detail below, the main R&D challenges arise from the very factors that lead to higher cycle efficiency. These include the use of: (1) elevated pressures throughout the cycle; (2) large duty heat exchangers to minimize the energy lost in cooling the working fluid; and (3) CO_2 as the working fluid. R&D will be needed to develop high efficiency CO_2 expansion turbines. These turbines offer the promise of relatively small size because of the low turbine pressure ratio and the high density of the working fluid, but this will be partially offset by the much higher mass flow rates required and the corrosion properties of high pressure CO_2. R&D will be required on seals, bearings, and materials, particularly in applications having elevated turbine inlet temperatures. R&D will also be needed to develop low cost heat exchangers that are able to attain large heat transfer duties with small temperature differences between the hot and cold sides of the exchanger and with a small pressure drop. This will require R&D into compact heat exchanger designs, assessment of materials for suitability given the temperatures and pressures required, and advances in manufacturing techniques.

Brayton Cycles based on CO_2 as the working fluid

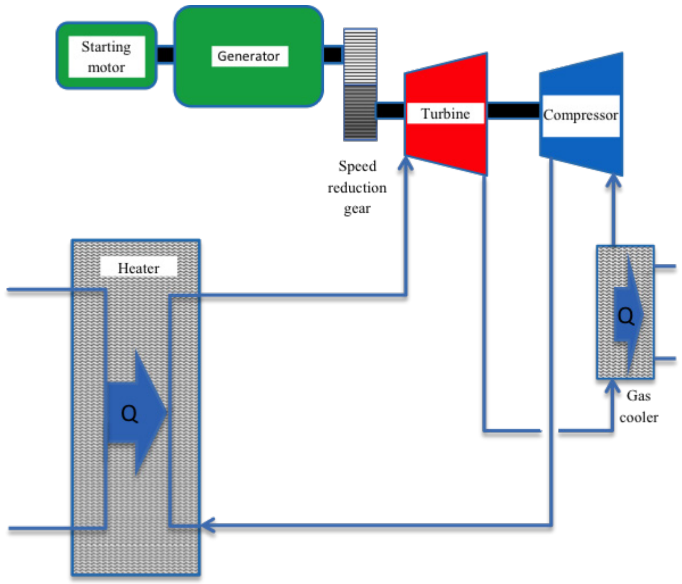
Power cycles using sCO_2 as the working fluid take on two primary configurations relevant to power generation: 1) an indirect-fired closed Brayton cycle that is applicable to advanced fossil fuel combustion, nuclear, and solar applications; and 2) a semi-closed, direct-fired, oxy-fuel Brayton cycle well-suited to fossil fuel oxy-combustion applications with CO_2 capture. These cycles are described in greater detail in the following sections.

Simple Indirect-fired Brayton Cycle

Figure 4.R.1 shows a block flow diagram for the simple indirect-fired Brayton cycle. A working fluid, which may be a pure substance or a mixture, circulates between a compressor and an expansion turbine. Thermal energy is added to the working fluid just prior to the expansion turbine and a cooler is required to lower the temperature of the working fluid after expansion to the desired inlet temperature to the compressor. In an ideal cycle, with an ideal gas working fluid and no irreversibility in the cycle, the cycle efficiency depends only on the cycle pressure ratio and increases monotonically with the pressure ratio.[4]

Figure 4.R.1 Block Flow Diagram for Simple Brayton Cycle

Credit: NETL



For non-ideal cycles, the cycle efficiency as a function of pressure ratio passes through a maximum at some pressure ratio which depends on the working fluid. Figure 4.R.2 shows the cycle efficiency as a function of pressure ratio for three different working fluids with an arbitrary turbine inlet temperature of 700°C. The dashed lines in the figure correspond to ideal cycles in which the turbomachinery isentropic efficiency (η) is 1 and the solid lines correspond to a non-ideal cycle with turbomachinery isentropic efficiencies of 0.9. For each of these cases, heat and pressure losses were neglected so the cycle efficiencies are optimistic. Note the large decrease in efficiency and the introduction of an efficiency maximum for non-ideal cycles compared to ideal cycles (see also Table 4.R.1).

Figure 4.R.2 Simple Brayton Cycle Efficiency. Plot of cycle efficiency versus pressure ratio for three different working fluids with ideal turbomachinery (dashed lines) and non-ideal cycles with turbomachinery isentropic efficiencies (η) of 0.9.[5]

Credit: NETL

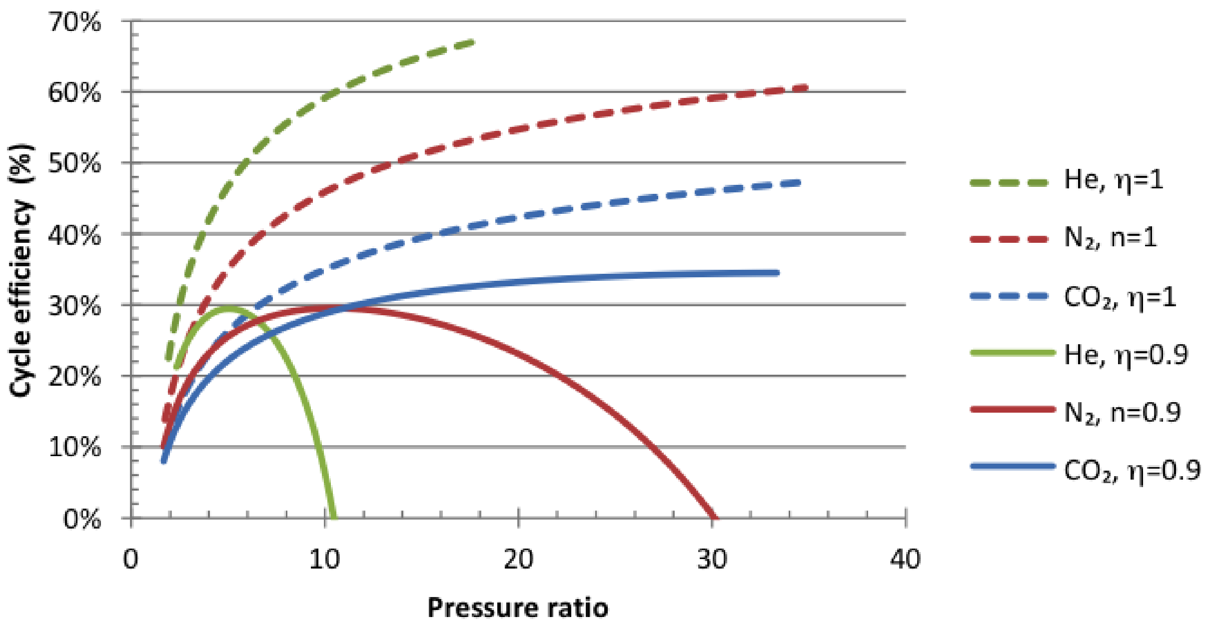


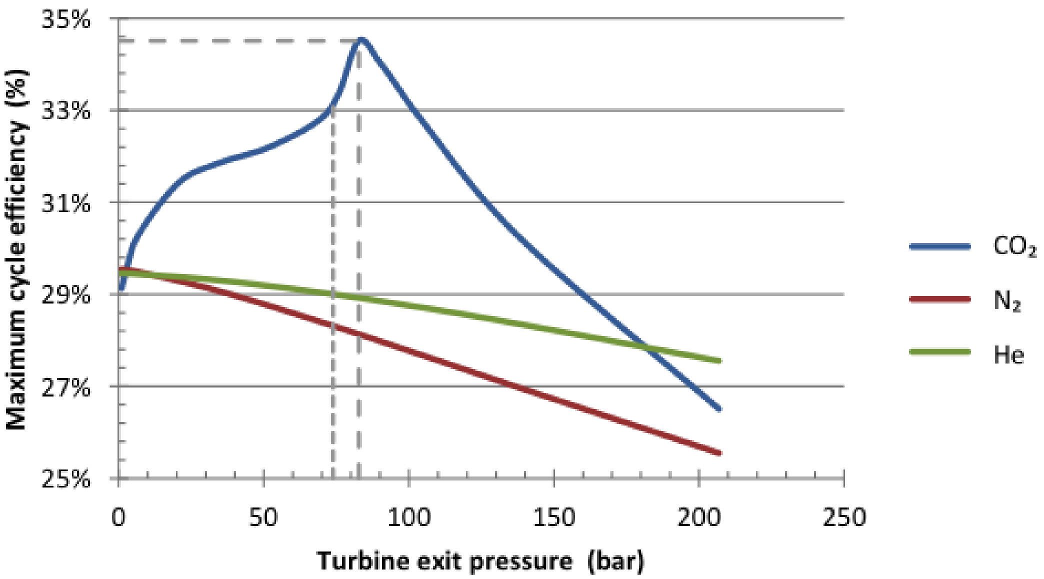
Table 4.R.1 Non-ideal Simple Brayton Cycle Performance[6] and Working Fluid Properties[7,8]

Working fluid	T_c (K)	P_c (bar)	c_p/c_v	Pressure ratio at maximum efficiency	Turbine exit pressure at maximum efficiency (bar)	Maximum efficiency (%)
CO_2	304	73.8	1.289	34.9	82.7	34.5
N_2	126	33.9	1.4	10.5	1.0	29.5
He	5	2.3	1.66	5.0	1.0	29.5

Another interesting aspect of the Brayton cycle based on CO_2 is that the cycle efficiency is strongly dependent on the minimum pressure in the cycle. Figure 4.R.3 shows the maximum cycle efficiency as a function of turbine exit pressure for three different working fluids with an arbitrary turbine inlet temperature of 700 °C and turbomachinery isentropic efficiencies of 0.9. For N_2 and He, the cycle efficiency decreases monotonically as the turbine exit pressure increases. For CO_2, however, the cycle efficiency shows a maximum of 34.5% when the turbine exit pressure is approximately 82.7 bar (right vertical dashed line in Figure), a bit above the critical pressure of 73.8 bar (left vertical dashed line in Figure). Note also that for a turbine exit pressure of 1 bar, the maximum cycle efficiency is nearly the same for all three working fluids.

Figure 4.R.3 Maximum Simple Brayton Cycle Efficiency varies strongly with turbine exit pressure for CO_2. Plot of cycle efficiency versus turbine exit pressure ratio for three different working fluids and turbomachinery isentropic efficiencies of 0.9.[9]

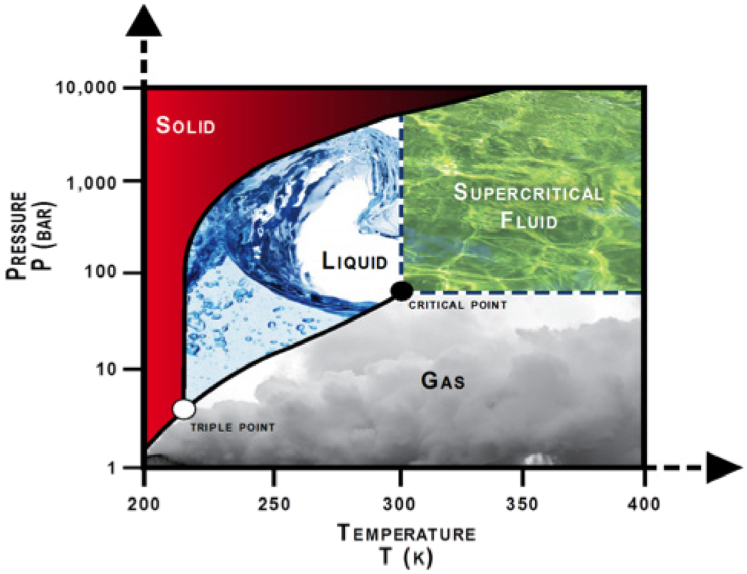
Credit: NETL



A thermodynamic critical point, as shown in a Phase Diagram (see Figure 4.R.4[10]) is the end point of a phase equilibrium curve. The end point of the pressure-temperature curve is of interest because this point designates conditions where a liquid and its vapor can coexist.[11] Table 4.R.1 lists the critical temperature (T_c) and critical pressure (P_c) for CO_2, N_2, and Ar. The key property of a fluid near its critical point is its higher gas phase density, closer to the density of a liquid than of a gas. With the CO_2 near the critical pressure at the point of entrance to the compressor, its density will be relatively high and the power requirement for compression will be lower. This directly increases cycle efficiency. Another advantage to maintaining the working fluid above the critical pressure is that the high fluid density throughout the cycle will lead to relatively high power density which is expected to significantly decrease the footprint and capital cost of the major pieces of equipment, although this may be offset by the need to utilize stronger and more expensive materials.

Figure 4.R.4 CO_2 Phase Diagram

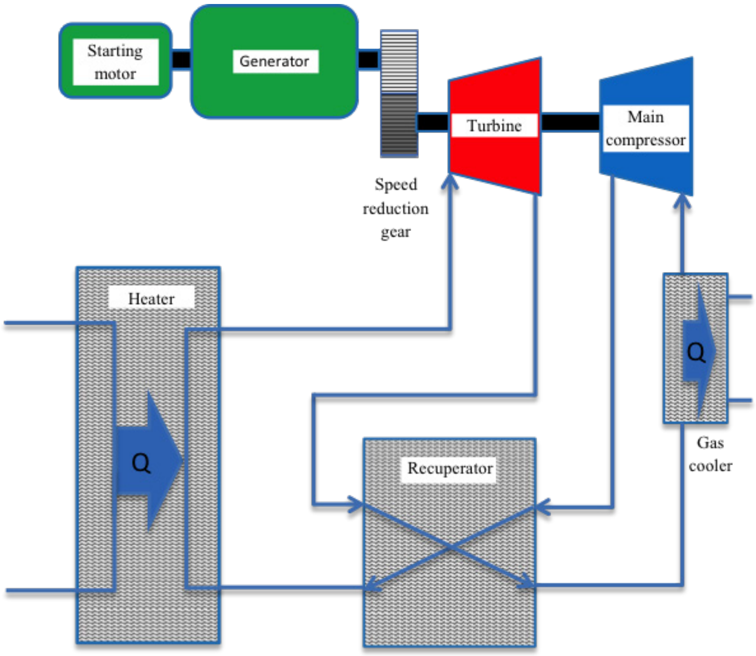
Credit: Wikimedia Commons



Recuperated Indirect-fired Brayton Cycle

Figure 4.R.5 Block Flow Diagram for Recuperated Brayton Cycle

Credit: NETL



A more advanced version of the indirect-fired Brayton cycle incorporates thermal recuperation. A block flow diagram for such a cycle is shown in Figure 4.R.5. The only change in the cycle is the introduction of a heat exchanger between the expander exhaust and the compressor exhaust. This heat exchange improves the cycle efficiency by reducing the amount of heat lost in the CO_2 cooler and increasing the amount of working fluid that can pass through the cycle for any specified amount of thermal input. A byproduct of this effect is that the pressure ratio for maximum cycle efficiency is considerably lower than for simple indirect-fired Brayton cycles. Figure 4.R.6 shows the cycle efficiency as a function of pressure ratio for three different working fluids with a turbine inlet temperature of 700°C (recuperated Brayton cycle—RB). The dotted curves show the cycle efficiency for a simple or non-recuperated Brayton cycle (simple Brayton cycle—SB). For all working fluids, the recuperated Brayton cycle has a higher efficiency than the corresponding simple Brayton cycle over the entire range of feasible pressure ratios. The maximum feasible pressure ratio for a recuperated Brayton cycle occurs at a much lower pressure ratio than for the simple Brayton cycle. This maximum pressure ratio occurs when the compressor outlet temperature equals the turbine exit temperature and further recuperation is no longer possible. For the recuperated Brayton cycle, the point of maximum cycle efficiency occurs at much lower pressure ratios than for a simple Brayton cycle. Although the CO_2 cycle has the lowest maximum cycle efficiency, the efficiency curve is relatively flat allowing for more stable operation. Table 4.R.2 shows the maximum cycle efficiencies.

Figure 4.R.6 Recuperated Brayton Cycle Efficiency. Plot of cycle efficiency versus pressure ratio for recuperated Brayton cycle (solid lines, RB) with three working fluids compared to the simple Brayton cycle (dashed lines, SB).[12]

Credit: NETL

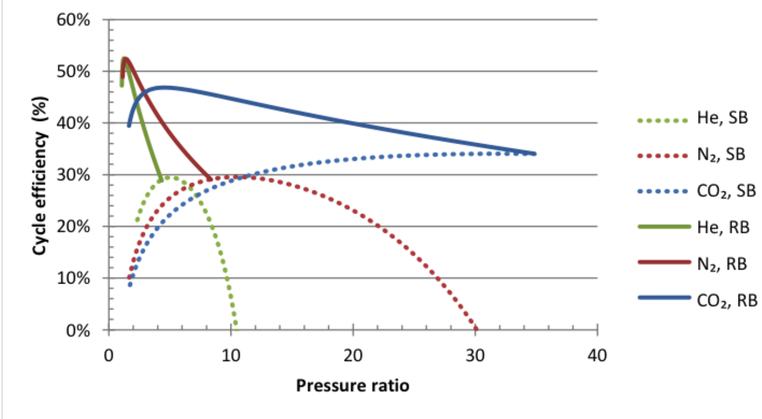


Table 4.R.2 Recuperated Brayton Cycle Performance Compared to Simple Cycle Performance [14]

Working fluid	Recuperated Brayton Cycle		Simple Brayton Cycle	
	Pressure ratio at maximum efficiency	Maximum efficiency (%)	Pressure ratio at maximum efficiency	Maximum efficiency (%)
CO_2	4.5	46.8	34.9	34.5
N_2	1.4	52.4	10.5	29.5
He	1.2	52.5	5.0	29.5

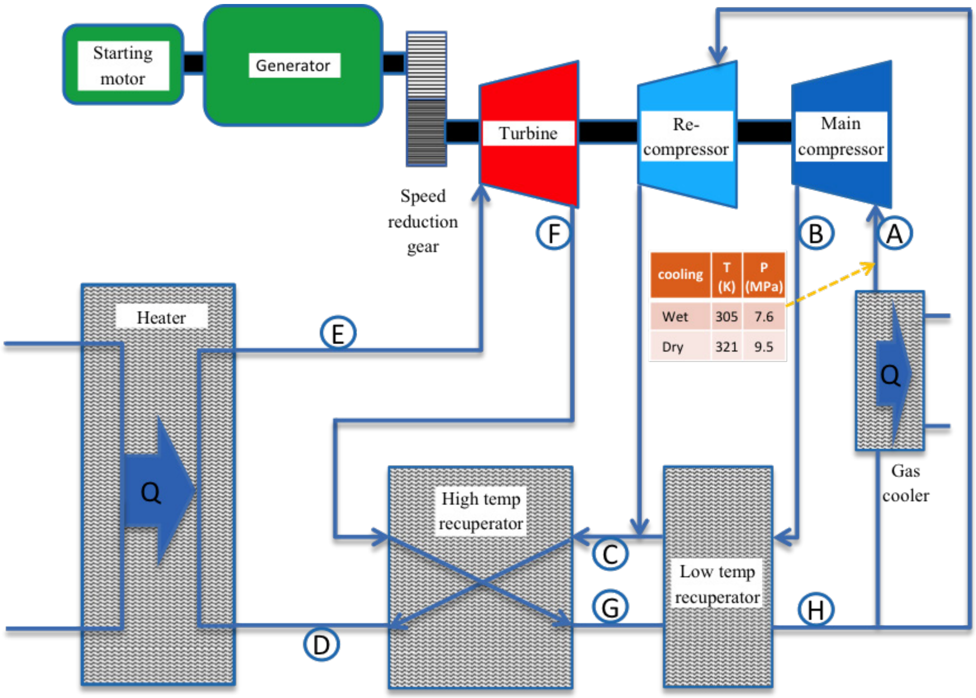
It is easy to show that for the recuperated indirect-fired Brayton cycle, the cycle efficiency increases with increases in turbine inlet temperature and turbo-machinery efficiencies, and decreases with increases in cycle pressure drop, heat loss, and minimum approach temperature in the recuperator.[13]

Recompression Indirect-fired Brayton Cycle

A secondary effect of having the minimum cycle pressure close to the CO_2 critical pressure is that it hampers the effectiveness of the recuperator somewhat. Near the critical point, the heat capacity of the CO_2 increases significantly and the hot CO_2 on the low pressure side of the recuperator does not have as high a thermal capacitance as the cold CO_2 on the high pressure side of the recuperator. This limits the maximum temperature that the recuperator can raise the high pressure CO_2 and acts to lower cycle efficiency. One approach to mitigate this effect is to use a recompression configuration for the cycle. Figure 4.R.7 shows the block flow diagram for the recompression indirect-fired Brayton cycle and Figure 4.R.8 shows the corresponding pressure-enthalpy diagram.

Figure 4.R.7 Block Flow Diagram for Recompression Closed Brayton Cycle.[15] The state points A through H are defined in Figure 4.R.8.

Credit: Sandia National Laboratories



The labeled points A-H in Figure 4.R.8 correspond to state points in the recompression Brayton cycle and are also depicted on Figure 4.R.7. The operating envelope shown in Figure 4.R.8 corresponds to a recompression sCO_2 Brayton cycle with a turbine inlet temperature of approximately 600°C and a cycle pressure drop of 700 kPa.

Points C-H in Figure 4.R.7 are the same as for the recuperated Brayton cycle. Where the recompression cycle differs is downstream of point H. In this configuration, a portion of the low pressure CO_2 exiting the recuperator bypasses the CO_2 cooler and is compressed to the maximum cycle pressure in a separate compressor from the main CO_2 compressor. In addition to bypassing the CO_2 cooler, this stream bypasses the low temperature portion of the recuperator. The net thermal effect is to provide a better match of thermal capacity between the hot and cold sides of the recuperator and increase the overall effectiveness of the recuperator. The disadvantage of this configuration is that the cycle is more complex and an extra compressor is required. While the total amount of power required for CO_2 compression actually increases in this configuration, the net cycle efficiency increase because more CO_2 can pass through the cycle for any given thermal input. Note that in Figure 4.R.7, two different values of the temperature and pressure are shown for state point A. These correspond to two different scenarios for the CO_2 cooler: a wet cooling case using water as the cooling medium, and a dry cooling case using air cooling. The dry cooling case has a lower efficiency than the wet cooling case but the efficiency reduction could be reduced by increasing the minimum cycle pressure.

Figure 4.R.8 Pressure Enthalpy Diagram for Recompression Closed Brayton Cycle.[16] The state points A through H are analogous to those shown in Figure 4.R.7.

Credit: Sandia National Laboratories

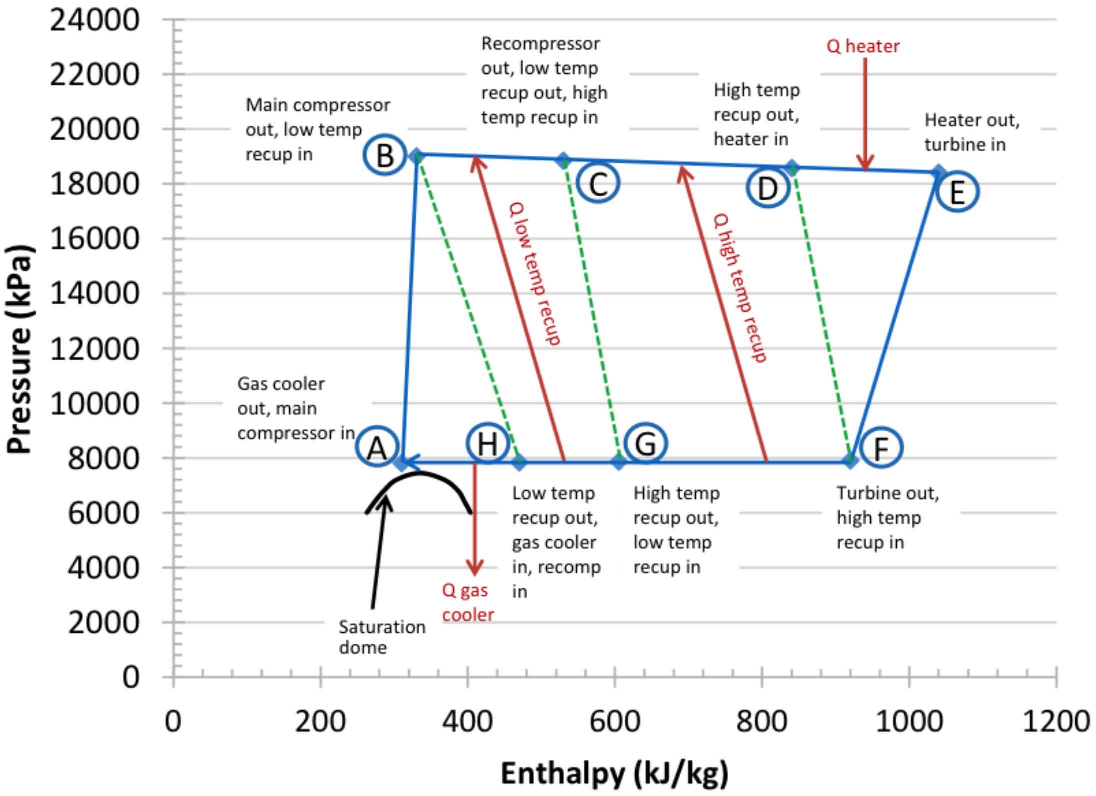


Figure 4.R.9 compares the cycle efficiency of the recompression CO_2 Brayton cycle (RCBC) with the recuperated Brayton cycle (RB) for CO_2 with a turbine inlet temperature of 700°C. The recuperated cycle efficiency curves for N_2 and He are also shown for comparison. For N_2 and He, the working fluid is not near the critical point at the exit of the cooler and so a recompression cycle offers no benefit.

For CO_2, at the pressure ratio of maximum cycle efficiency, the efficiency of the recompression cycle is over 5 percentage points higher than the recuperated Brayton cycle. Table 4.R.3 compares the maximum cycle efficiency for the recompression Brayton cycle compared to the recuperated Brayton cycle for the three working fluids.

Figure 4.R.9 Recompression Brayton Cycle Efficiency.[17] Plot shows cycle efficiency versus pressure ratio for RCBC (solid line) and Recuperated Brayton Cycle (dashed lines, RB).

Credit: NETL

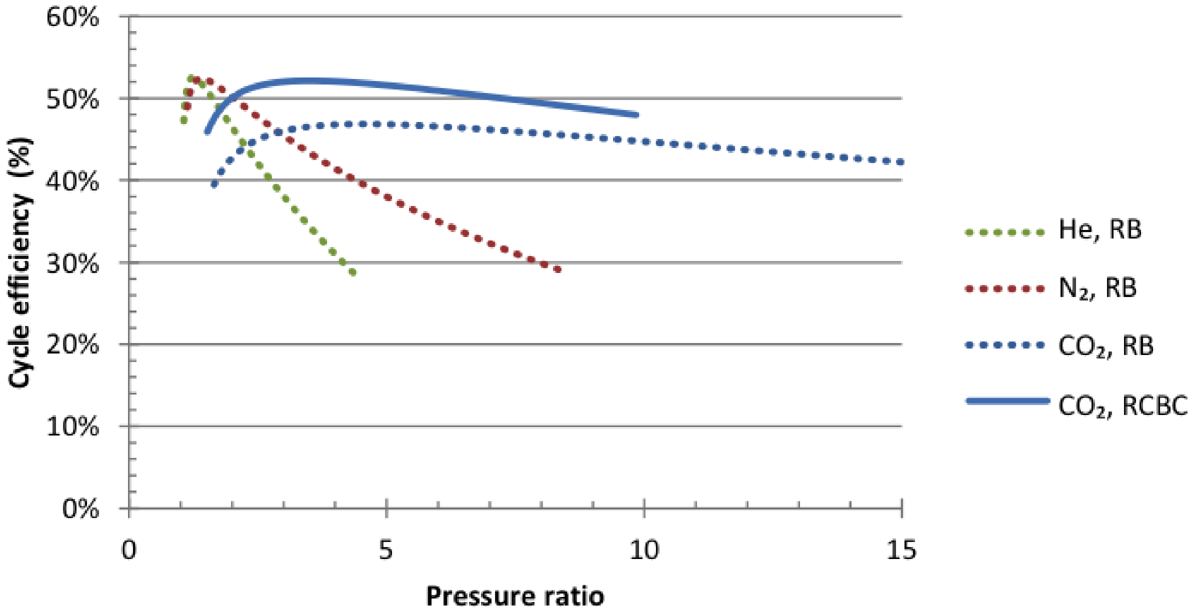


Table 4.R.3 Recompression Brayton Cycle Performance Compared to Recuperated Cycle Performance[18]

Working fluid	Recompression Brayton Cycle		Recuperated Brayton Cycle	
	Pressure ratio at maximum efficiency	Maximum efficiency (%)	Pressure ratio at maximum efficiency	Maximum efficiency (%)
CO_2	4.4	52.1	4.5	46.8
N_2	1.4	52.4	1.4	52.4
He	1.2	52.5	1.2	52.5

Recompression sCO_2 Brayton Cycle versus Rankine Cycle

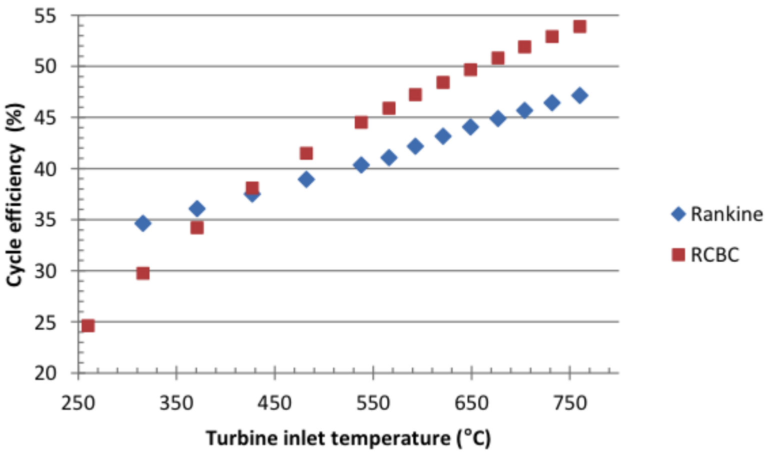
A direct comparison of the conventional Rankine cycle with the RCBC is difficult because the Rankine cycle is an established and mature technology and has undergone a century of development and refinement. The state-of-the-art in Rankine cycles today is the ultra-supercritical (USC) cycle having a main steam pressure of 250-290 bar and temperature of 600°C with a reheat temperature of 620°C. Since there are no commercial scale power plants based on the RCBC, any comparison must be based on assumptions about the operating point.

Although the nature of these two cycles is different, they both exhibit an increase in efficiency as the turbine inlet temperature increases. However, the magnitude of that increase will be different for the two cycles and hence each cycle will have a range of turbine inlet temperatures over which its efficiency is higher than the other cycle. There have been some limited comparisons of the performance of these two power cycles in the literature[19,20] and they consistently show that the RCBC has a higher cycle efficiency at moderate to high values of the turbine inlet temperature. The exact value of the turbine inlet temperature where the RCBC attains a higher efficiency will vary depending on the selected cycle configurations and assumptions used for the operating state for the RCBC.

Figure 4.R.10 shows the results of a systems analysis performed at NETL comparing the RCBC with a Rankine cycle having a single reheat. In this analysis the turbomachinery efficiencies for the two cycles were made equal. The results show the same trend as in prior studies and show that the RCBC has a higher efficiency than the Rankine cycle when the turbine inlet temperature exceeds approximately 425°C.

Figure 4.R.10 Comparison of Recompression Brayton Cycle and Rankine Cycle Efficiencies[21]

Credit: NETL



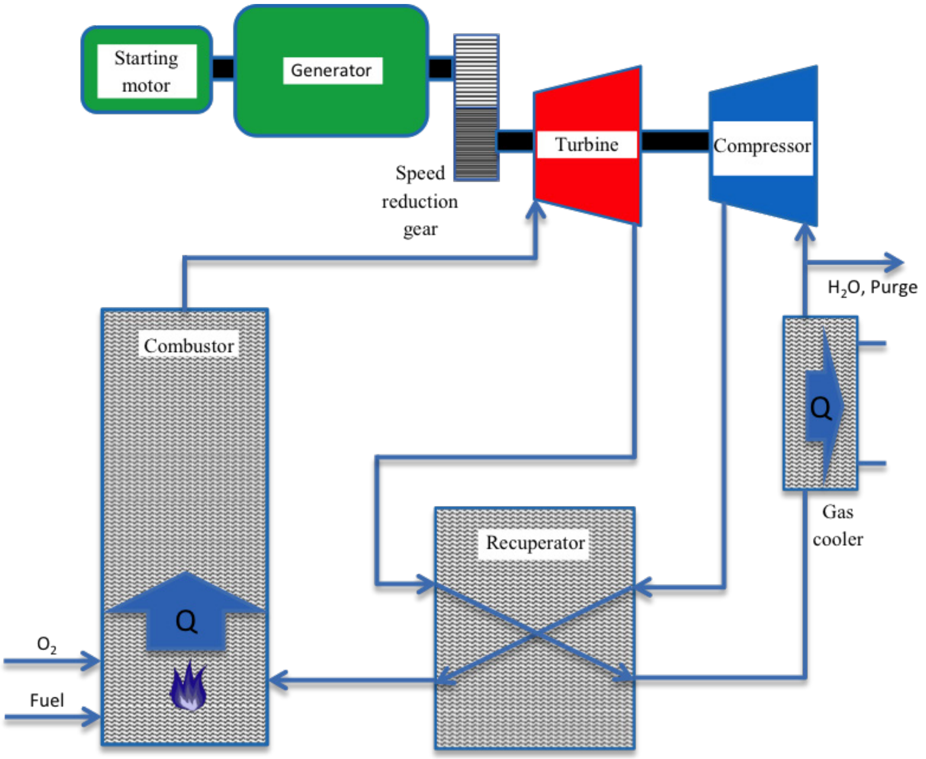
Semi-closed Direct-fired Oxy-fuel Brayton Cycle

In addition to the indirect-fired cycles described previously, direct-fired Brayton cycles using CO_2 as the working fluid are being actively investigated for fossil energy applications. Figure 4.R.11 shows a simplified block flow diagram for this cycle. The heat source is replaced with a pressurized oxy-combustor and hence, the working fluid is no longer high-purity CO_2. Since much of the performance benefit of sCO_2 cycles derive from the physical properties of supercritical CO_2, the cycle efficiency will decrease as the concentration of CO_2 decreases and hence a relatively pure and near stoichiometric oxygen stream is advantageous. This will also have the benefit of facilitating the capture of the CO_2 generated during combustion, as part of a carbon capture and storage (CCS) process. The fuel for such a system may be synthesis gas (syngas) produced by a coal gasifier[23] or natural gas.[24,25]

As with the indirect-fired cycles, the working fluid is recycled with thermal recuperation but the combustion products must be removed from the working fluid prior to the recycle. This is expected to be accomplished through a cooling step to condense and remove water and a purge of a portion of the working fluid to remove the material introduced by combustion, including the CO_2 generated, excess oxygen, and other contaminants from

Figure 4.R.11 Block Flow Diagram for Semi-closed sCO_2 Brayton Cycle

Credit: NETL



the oxidant or the combustion reactions. Semi-closed direct-fired oxy-fuel Brayton cycles offer the possibility for significantly higher cycle efficiencies than the indirect cycles due to the significantly higher turbine inlet temperature that can be achieved in a direct-fired cycle. They are also expected to have a higher power density than the indirect-fired cycles and will be simpler since a recompression bypass compressor is not needed.

Advanced sCO_2 Power Cycles

Both the indirect and direct sCO_2 power cycles are amenable to additional enhancements that can further increase the cycle efficiency. For example, the indirect cycle efficiency may increase with the use of reheat and/or compressor intercooling.[26] Some studies have suggested that lowering the CO_2 cooler pressure below the critical pressure and condensing the CO_2 into a liquid state will increase cycle efficiency since the power required to pump a liquid is much less than the power required to compress a gas.[27] Cycle configurations have also been proposed that will increase the range of temperatures over which heat can be harvested in the power cycle. This may be particularly advantageous with fossil fuel heat sources.

Brayton Cycles based on Other Supercritical Fluids

The supercritical recompression Brayton cycle could utilize working fluids other than CO_2. However, several factors limit the number of candidate fluids for a practical power cycle. To maintain high fluid density through the compression phase, and hence high cycle efficiency, the cooler must operate near the critical point of the fluid. Since cycle efficiency will increase as the cooler temperature decreases, fluids having a critical temperature that can be attained with coolants readily-available for power plant use (e.g., ambient temperature water) will have an advantage – in this regard, sCO_2 (critical temperature of 304K, or 87°F) is well-suited. Also, the critical pressure must be well below the maximum pressure in the cycle and this further limits the number of candidates. When other factors such as safety, thermal stability, corrosion, and cost are factored in, the number of candidate working fluids is quite small. Although extensive analyses have been performed,[29] no other potential working fluids have been identified that are better candidates for the supercritical recompression Brayton cycle than CO_2 for terrestrial applications.

sCO_2 Brayton Cycles – Summary and Application Areas

A number of Brayton cycle configurations using sCO_2 have been described and their performance characteristics highlighted. sCO_2 Brayton cycles have a clear potential to attain higher cycle efficiencies than conventional steam Rankine cycles, non-supercritical Brayton cycles, or geothermal power cycles. This is achieved primarily by selecting the cycle operating conditions to minimize the power requirement for compressing the working fluid and by using a high degree of thermal recuperation.

The range of potential applications for the indirect sCO_2 Brayton cycle is broad since it can be used in essentially any application that currently uses a Rankine cycle. Generally, the operating conditions where the recompression sCO_2 Brayton cycle attains its highest efficiency requires a large degree of thermal recuperation. This reduces the heat loss in the CO_2 cooler and allows the heat source to heat the maximum amount of working fluid and hence, generate the maximum amount of power output. A potential disadvantage of this high degree of recuperation is that the temperature increase of the CO_2 in the heat source is relatively low. If the hot source operates across a wide temperature range it will create challenges in maintaining high cycle efficiency without discarding a significant portion of the available hot source energy. Many of the promising applications for indirect sCO_2 Brayton cycles have heat sources that have a narrow temperature range. Examples include applications with nuclear, solar, and geothermal heat sources. In each of these cases, the sCO_2 Brayton cycle operating state can be configured to utilize the maximum amount of energy available from the hot source. When the hot source temperature range is large, more complex modifications to the cycle are generally required. This may entail a higher degree of process-level heat integration, or reduction in cycle recuperation to increase the amount of hot source energy that can be utilized in the cycle, or employing a more complex cascade cycle configuration, or possibly using a combined cycle process in which the sCO_2 Brayton cycle serves as the topping cycle and a Rankine cycle is used as a bottoming cycle. Conceptual designs have been proposed for each of these alternatives.[30,31,32]

The sCO_2 Brayton cycle can also be configured for direct heating which increases its range of potential applications. The most promising application areas for direct cycles are with fossil fuel sources. Although it is overall process efficiency and not cycle efficiency that will determine whether a given power generation system is more efficient, for many applications it is straightforward to demonstrate that a higher cycle efficiency will lead to a higher process efficiency. This is because the fraction of energy from the heat source that can be harvested by the power cycle is generally not diminished with the sCO_2 Brayton cycle and there is generally not an increase in the balance of plant auxiliary power required by the plant for the sCO_2 Brayton cycle compared to Rankine cycles. Direct cycles also provide an intrinsic method to capture the water generated during combustion, as liquid water which will partially offset the water withdrawal in a water-cooled application. Oxy-fired direct cycles for fossil fuel applications have the additional benefit of facilitating CO_2 capture, significant given the EPA's Carbon Pollution Standards, issued under the authority of Section 111(b) of the Clean Air Act in August, 2015, that limit CO_2 emissions from new coal-fired power plants to 1,400 lb CO_2/MWh-gross.[33]

Table 4.R.4 provides a listing of the major categories of applications for the sCO_2 Brayton cycle, the expected cycle configuration, the peak temperature for the working fluid, and the major benefits the sCO_2 Brayton cycle may potentially demonstrate in each application.

The principal benefit of the sCO_2 Brayton cycle is the potential for an increase in both cycle and process efficiency compared to processes that employ Rankine cycles. An increase in process efficiency has many secondary benefits including a reduction in the thermal input needed to generate a fixed amount of power

Table 4.R.4 Potential Applications for sCO_2 for Power Conversion – Modified from Workshop[34]

Application	Cycle type	Motivation	Size [MWe]	Temperature (°C)	Pressure [MPa]
Nuclear	Indirect sCO_2	Efficiency, Size, Water Reduction	10 - 300	350 - 700	20 - 35
Fossil Fuel (PC, CFB, …)	Indirect sCO_2	Efficiency, Water Reduction	300 - 600	550 - 900	15 - 35
Concentrating Solar Power	Indirect sCO_2	Efficiency, Size, Water Reduction	10 - 100	500 - 1000	35
Shipboard Propulsion	Indirect sCO_2	Efficiency, Size	<10 - 10	200 - 300	15 - 25
Shipboard House Power	Indirect sCO_2	Efficiency, Size	<1 - 10	230 - 650	15 - 35
Waste Heat Recovery	Indirect sCO_2	Efficiency, Size, Simple Cycles	1 - 10	< 230 - 650	15 - 35
Geothermal	Indirect sCO_2	Efficiency	1 - 50	100 - 300	15
Fossil Fuel (Syngas, nat gas)	Direct sCO_2	Efficiency, Water Reduction, CO_2 Capture	300 - 600	1100 - 1500	35

which lowers the size and capital cost, and for some applications, also lowers the fuel usage and operating costs. Increasing process efficiency also diminishes the environmental footprint of the process by reducing water usage and in the case of fossil fuel applications, reducing greenhouse gas emissions.

There are other potential benefits of the sCO_2 Brayton cycle as well although they remain to be demonstrated as convincingly as the potential for higher process efficiency. Because of the relatively high density of the working fluid, there is a potential for some of the unit operations to be smaller and less costly on a $/kWe basis. However, not all of the properties of the sCO_2 Brayton cycle lend themselves to size and cost reductions. For example, the sCO_2 Brayton cycle is more complex than the Rankine cycle, requires compressors instead of feedwater pumps, and requires recuperators having larger heat duties than the heat source.

Another potential benefit is that the sCO_2 Brayton cycle may prove to be more practical than the Rankine cycle for air cooling in locations where water cooling is not available.[35] This is because the working fluid cooler in the sCO_2 Brayton cycle requires significantly less air flow than an air-cooled condenser in a Rankine cycle having the same cooling duty. However, this benefit is achieved through reduction in the average driving force for heat transfer in the cooler which would act to increase the required surface area for heat transfer and some investigators have questioned the practicality of air cooling in the sCO_2 Brayton cycle.[36] With further analysis, development, and demonstration, the impact of this technology on power plant costs and water usage will become clearer.

In summary, the supercritical CO_2 based recompression Brayton cycle offers the opportunity to increase cycle efficiency compared to Rankine cycles and some other Brayton cycles and lead to power plants with higher process efficiency. CO_2 appears to be an ideal working fluid because it has a critical point well-suited to terrestrial applications with a moderate critical pressure and a critical temperature that is low enough to be reached with ambient cooling when the wet cooling option is available. The supercritical CO_2 Brayton cycle may be applied to direct-heating applications, with potential for high efficiency and capture of process water - such a cycle also facilitates CO_2 capture from the combustion process. When its availability and low cost are factored in, no other substance is a more attractive working fluid for the supercritical Brayton cycle.

While some progress has been made in researching and developing sCO_2 systems, significant challenges remain in areas such as material performance, manufacturing, economics, and reliability.

Technology Readiness and R&D Needs

Technology readiness is a function of the application (e.g., fossil, nuclear, concentrating solar thermal power, geothermal), the cycle concept (indirect versus direct cycles), the operating temperature (e.g., high vs low turbine inlet temperatures) and the plant scale (e.g., small 10 MWe systems vs large utility scale plants). Figures 4.R.7 and 4.R.11 illustrate block flow diagrams for the indirect and direct cycle. The system components requiring research and development include CO_2 turbines, recuperators, and CO_2 heaters. The technology readiness is grouped into three categories:

- Mature components: cycle components that do not contact sCO_2
- Less-mature components
- System integration

R&D needs are discussed in the following categories: mature components, less-mature components, system integration, and specific technology development needs.

Mature Components

In general, components that will not contact the sCO_2 working fluid are mature technologies. Design optimization appropriate for a given application would be required, but none of these components appear to present an obstacle to commercial deployment, and they can be assumed to be reasonably predictable in their cost, reliability, and performance. Mature subsystems and components include:

- Electrical generation subsystem
- Gearbox
- Heat rejection subsystem
- sCO_2 inventory control
- Plant controls
- Instrumentation
- High power electronics

Less Mature Components

The immature components can be sub-grouped into the indirect cycle needs and the direct cycle needs. The indirect cycle needs include the CO_2 turbine, the recuperators, and the CO_2 heater. In addition to the CO_2 turbine and recuperators, the direct cycle will require R&D on: (1) advanced pressurized oxy-combustion; (2) extreme turbine inlet temperatures and associated challenges with turbine materials and blade cooling; (3) more extensive thermal integration at the cycle and process level; (4) sub-critical CO_2 pumping and compression; and (5) perhaps additional challenges in fuel processing.

CO_2 turbines

A significant technology gap is that there are no utility-scale sCO_2 turbines and operational experience at any scale is limited. The fundamental scientific basis and engineering tools for turbine and compressor design are fairly mature and reliable. Thus, there are not expected to be any insurmountable obstacles but it still has to be designed and tested. Compared to an air breathing turbine, the sCO_2 design must account for differences in heat capacity, density, viscosity, and acoustic properties. Particular challenges include materials, seals, corrosion, erosion, and blade cooling (for turbine inlet temperatures greater than nominal 1400°F [760 °C]). The trade-off between operating at a high turbine inlet temperature that promises high efficiency and the development challenge is an important system analysis consideration.

The high density, high pressure, and rapidly changing material properties of CO_2 near the critical point represents a relatively new and very different regime for turbomachinery design. The small-scale sCO_2 research turbines and compressors developed to date have performed very close to the design maps generated from first principles and have operated effectively above and below the critical temperature without the typical mechanical slugging that occurs with steam. Therefore, it is anticipated that there will not be major surprises in the turbomachinery design and operating efficiency as the technology is scaled up to higher power levels, but high quality designs and precision machining of both the compressor wheel and turbine wheel are essential to achieving high component efficiency and resulting high system efficiency. Selecting the scale for testing is also important in order to simplify turbomachinery scale-up. Figure 4.R.12 shows the effect of design on turbomachinery capacity. A nominal 10 MWe capacity is selected as a pilot scale capacity to facilitate effective scale-up.

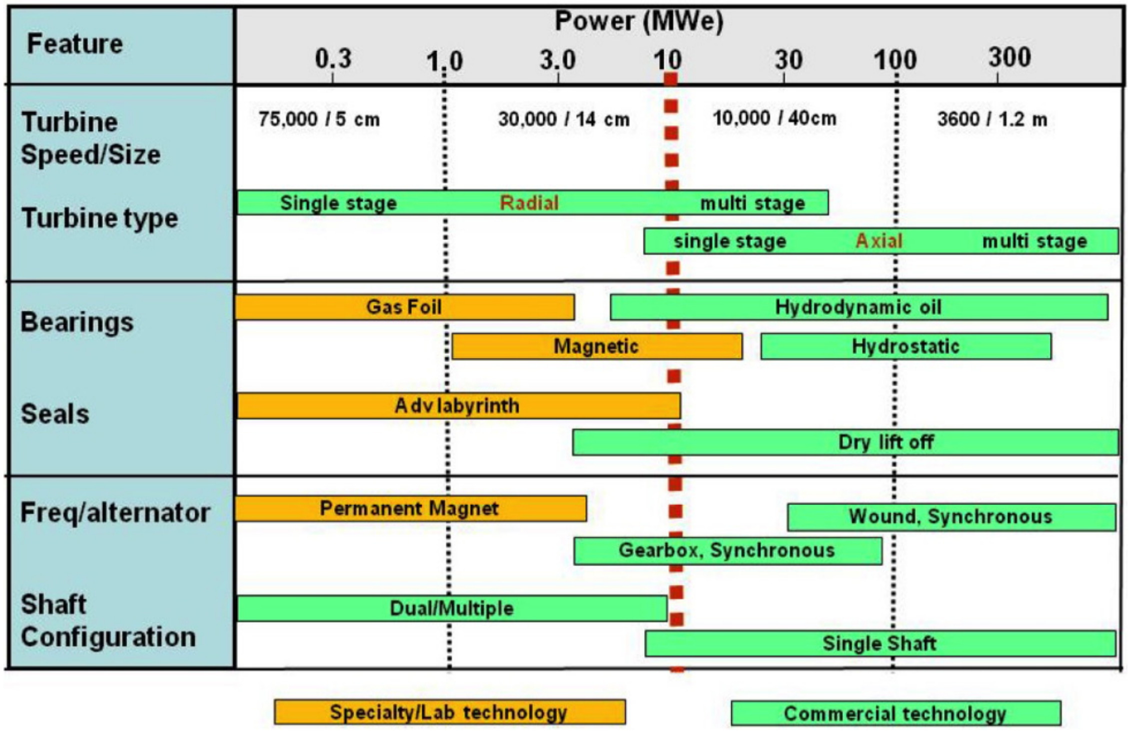
Recuperators

Internal heat transfer through recuperation significantly increases the efficiency of a cycle with fixed turbomachinery conditions by reducing the amount of external heating and cooling required by the cycle. The technical challenge is determining the optimal cycle design, balancing increases in efficiency with the increased system costs as more recuperation is added.

A major constraint to the design is to avoid a large pressure drop along each leg of the heat exchanger, while pursuing high heat transfer effectiveness. The design must accommodate high operating temperatures and pressures, and reductions in costs need to be demonstrated. In addition, maturing manufacturing processes will be needed to address diffusion-bonding techniques, investment-casting research, and in-service inspections as it relates to manufacturing economics.

Figure 4.R.12 Ranges of Application for Key Brayton Cycle Turbomachinery Components and Features[37]

Credit: Sandia National Laboratories



CO_2 Heaters

More so than for any other component, the design of and associated developmental challenges of the CO_2 heater will depend on the individual application and heat source. Of particular importance to the heat source is the temperature profile.

For indirect sCO_2 Brayton cycles, the final stage of heating the CO_2 before it enters the turbine poses a similar set of challenges as for recuperators. While analogs exist in the existing Rankine cycles, the CO_2 heater poses additional engineering challenges. The heat capacitance of the CO_2 is much lower than water on a weight basis. Compounding this problem is the fact that the average driving force for heat transfer (i.e., temperature difference between the hot side and cold side) in the CO_2 heater is expected to be much lower than the comparable driving force in a Rankine cycle boiler. This means that the required heat transfer area will be much greater. The need for a design that minimizes pressure drop is just as important for the CO_2 heater as for the recuperators.

With indirect fossil-fueled combustors and bottoming cycle applications, the heat source temperature profile will be very broad and the sCO_2 cycle configuration will need to allow for the absorption of sensible heat from the flue gas down to a low level. Otherwise, a high cycle efficiency will be wasted due to a low overall recovery.

In the direct-fired cycles, the driving forces are expected to be much higher but so too will be the final temperature of the heated CO_2. A perhaps more significant challenge is designing the oxy-combustor for high pressure operation with a minimum amount of excess oxygen.

System Integration

For any given application, system integration is an important development effort that will be needed to optimize the operating and design parameters of the cycle and address start-up, shut-down, transient, and part-load operation. Dynamic processes within the system, such as pressure surging, heat transfer and convection, turbulent flow conditions, pressure waves, and acoustics must be considered for the integrated plant operation. System integration also requires taking into account the effects of unavoidable impurities in the sCO_2 working fluid such as carbon monoxide and water vapor on the critical properties of pure carbon dioxide, such as forming carbonic acid.

Specific Technology Development Needs

The following provides examples of specific fundamental R&D needs.

Turbomachinery

As noted above, seals and bearings illustrate two specific technology development needs for achieving reliable and economic turbomachinery.

Seals: Both the turbine and the compressor shafts of sCO_2 systems must penetrate high pressure boundaries yet have minimal friction to their rotation. This has not been demonstrated at the pressures and temperature needed for sCO_2 applications, nor at the power levels required by industry (10 MWe to 1,000 MWe). A potential solution is to isolate the shaft seals for the generator, radial, and thrust bearings, and any necessary starter motors from the high pressure/high temperature CO_2 environment. Placing these components outside the high pressure/high temperature environment would allow use of industry standard bearings whereas keeping them inside leads to shorter shaft lengths and improved rotor dynamics.

Commercial experience with sCO_2 shaft seals to date is largely based upon CO_2 transport and injection operations in support of enhanced oil recovery. This application has been successfully met in a range of low temperature supercritical fluid conditions at low to moderate shaft speeds (3,600 to 8,000 rpm) by non-contacting CO_2-film dry-gas seals. Off-the-shelf solutions for high pressure sCO_2 sealing do not presently meet the requirements for the high temperatures that would be required at the turbine end of a sCO_2 power cycle.

Bearings: Proper design and selection of bearings is frequently one of the most important factors to turbomachinery system performance and reliability. The technical challenge is to determine the approach that is suitable for the conversion system and develop a specific configuration that results in acceptably low frictional loss and also survives the corrosion and erosion environment. A number of different technologies may be considered, but, for high-speed, high-load applications such as power production turbomachinery, fluid film (hydrodynamic) bearings and rolling element bearings have historically been the industry workhorses.

Materials

Each application will have specific material design and code requirements. For example, ASME Code Section III stipulates that only five materials may be used for construction of nuclear reactor components for high temperature service. The use of the high-temperature nuclear construction materials will be required for all the components of the primary and secondary systems of advanced nuclear plants. However, it is not clear where the boundary of material use for the balance-of-plant will be drawn and where other materials may be used. Corrosion considerations for the use of the Section III high-temperature nuclear construction materials and for the use of materials in Sections I and VIII power boilers and unfired pressure vessels are not addressed by the ASME Code, other than by the general requirement stating that such corrosion shall not compromise the required section thickness or strength of the components.

Materials reliability uncertainties include: carburization and sensitization, high-temperature corrosion, erosion, creep, and fatigue. The effects of material interactions can impact the design, reliability, and lifetime of essentially all system components. These uncertainties and R&D needs are discussed below.

Carburization and Sensitization: Internal carburization and sensitization is a long-term concern for conventional austenitic stainless steels such as types 321 and 347, but is less of a concern for higher alloyed materials like alloy 709 and Ni-base alloys where the solubility of C is much lower. Similar carburization of ferritic-martensitic steels also has been observed at 550°-650°C. If these less expensive ferritic-martensitic and austenitic steels are to be used, R&D is needed on the long-term carburization behavior and maximum use temperature of these alloys to identify degradation mechanisms and for prediction of useful life.

High Temperature Corrosion: Based on relatively short-term oxidation tests, the high-temperature oxidation behavior of candidate advanced ultra-supercritical steam cycle (A-USC) alloys was found to be as good as, or better, in sCO_2 than in sH_2O, making them candidate alloys for indirect sCO_2 power cycle components also. These leading alloy candidates need to be tested for longer time periods (e.g. 1,000-5,000 hours) at 20-35 MPa at target temperatures (650-750°C) in sCO_2 to establish oxidation reaction kinetics and quantify the rate of internal carburization. Furthermore, the long-term effect of various joining techniques (e.g. diffusion bonding, brazing, etc.) on reaction rates needs to be determined. For the direct-fired concept, only information at 1 bar is available on how impurities such as O_2, H_2O, and others introduced in the CO_2 stream from the combustion of fuel may affect corrosion rates. Thus, oxidation/corrosion data results in supercritical conditions are needed.

Erosion: Erosion is a significant issue for the closed Brayton Cycle systems at two sCO_2 test facilities: SNL and Bettis. Substantial erosion in the turbine blade and inlet nozzle has been observed. It is believed that this is caused by residual debris in the loop and/or small particulates that originate from the spallation of corrosion products of different materials and at different locations within the loop. These particles are entrained through the nozzle vane and turbine, thus causing erosion. The problem in sCO_2 cycles is exacerbated by the fact that

sCO_2 is nearly twice as dense as supercritical steam and moves 11 times faster (in terms of mass flow rate) than supercritical steam in their respective systems. Thus, the compact size of the turbomachinery in the sCO_2 cycles results in a flow of a high density fluid at very high velocities. Owing to turbine speeds remaining constant, the issue of erosion is expected to be encountered in scale-up. In addition, inspection of the printed circuit heat exchanger within the closed Brayton Cycle system found an agglomeration of hydrocarbons and erosion products at the inlet.

To address the erosion issues in gas and steam turbines, a wide variety of coating systems have been explored by industry and various erosion-resistant coatings are in commercial use today. The selection of an appropriate coating system depends on the underlying substrate metal as well as (perhaps more importantly) on the source and properties of the particulate causing the erosion. For example, Bettis employs a procedure that filters the CO_2 five times before use.

Creep and Fatigue: Creep, the tendency of a solid material to deform slowly and permanently as a result of mechanical stresses below its yield strength at elevated temperatures, and fatigue, a failure mechanism that occurs when the component experiences cyclic stresses or strains that produce permanent damage, are primary potential limitations that must be accommodated in the design of sCO_2 systems. R&D to better understand creep and fatigue associated with sCO_2 turbomachinery and heat exchange components is necessary. In the turbomachinery, the gaps between the turbine and compressor wheels and their housings are small, the tip speeds are large, and the temperature (in the turbine) is high. Thus, creep and fatigue become lifetime issues. In the compact heat exchangers used as recuperators or primary heaters in the sCO_2 cycles, the pressure difference between the hot and cold legs is large (up to about 25 MPa), and the design goal is to minimize the wall thickness between them to maximize heat transfer and minimize cost while keeping flow passages small and numerous. If the system design constraints drive designs to more-corrosion resistant materials (e.g., due to CO_2 interactions), there may be a need to obtain creep rate data for those materials if sufficient data are not available from the manufacturer. Furthermore, diffusion bonding or brazing is used to join the layers of sheets to construct these compact heat exchangers. The diffusion bonded regions (usually less than 50μm thick) of the sheet material may have different chemical composition and microstructure compared to the rest of the sheet material resulting in different mechanical properties. Creep and fatigue behavior of joints (diffusion bonded or brazed) may need to be investigated as a part of the design methodology of compact heat exchangers. In addition to creep and fatigue as purely mechanical considerations as discussed, above the effect of the environment on these mechanical properties may need to be evaluated. For example, how carburization and oxidation of alloys in sCO_2 affect the creep rate and fatigue crack growth rate should be investigated. Also, for wall thicknesses below 0.5mm it should be recognized that creep behavior can be significantly different than for bulk material and relatively little information is available on some classes of material in thin sections, particularly the precipitation strengthened Ni-base alloys. Considerable expertise in evaluating creep properties of thin-walled steels and conventional Ni-base alloys for gas turbine recuperators (i.e. heat exchangers) was developed during the development of the Mercury 50 turbine and that information and expertise would be useful for the development of sCO_2 recuperators.

Valves

Any closed Brayton Cycle will require three valve functions: isolation, modulating/throttling, and pressure relief. The isolation and throttling valves are highly engineered and are, therefore, the highest cost valves. Operating mechanisms for these systems exist, but the valve body, internal components, and seat will be immersed in hot sCO_2 and subject to materials effects that create uncertainty regarding the design of the valves, requiring R&D. The valve actuator seals will require R&D to demonstrate that they can survive the hot sCO_2 environment.

Market Opportunities

The recompression sCO_2 Brayton cycle allows the extraction of thermal energy at a high temperature differential, while compression at relatively high density results in low parasitic compression work, contributing to the high efficiency of the cycle and the anticipated lower capital cost due to reduced size. The market includes diverse applications, opportunities for improved economics, and expanded market potential with successful R&D. Benefits that would accrue from successful R&D of the sCO_2 power conversion cycle include the following:

1. **Diverse applications:** The recompression sCO_2 Brayton cycle can be configured to operate with a variety of heat sources including nuclear, fossil-fuel, renewables such as concentrating solar thermal power (CSP) and geothermal, and waste heat, offering a very broad range of applications.
2. **Improved economics:** The sCO_2 Brayton cycle technology, with successful R&D, may be able to provide improved overall economics and operating conditions (e.g., higher efficiencies [lower fuel costs, lower GHG emissions], lower capital costs, reduced water usage) across various applications, infrastructures, and scales.
3. **Market growth through successful R&D:** Initial R&D activities are expected to result in technological and economic advantages for subsystems and components, which will help influence early industry participation and commercial adoption at the component level. As R&D activities advance beyond an initial demonstration, the technology is expected to achieve higher operating temperatures, allowing for increased potential market opportunities at scalable levels of power generation. At this point, both the full-system and new sub-components/technologies (that apply to larger scales and higher temperatures) may be adopted by industry. Later RD&D activities will leverage industry and stakeholder input and are expected to result in an increase in demand (once technical risks are resolved) for a full-system at low MWe levels.

In 2013, a commercialization review for sCO_2 Brayton cycle technology found that, if successfully developed, it could have applicability across various power generation applications and might offer significant economic advantages over current technologies.[38] Due to the technical challenges briefly described above and associated uncertainties in technology development, cost, and performance, market projections are highly speculative and additional research is required to better understand initial applications as well as applications where industry demand would be highest. An extensive market review with industry stakeholders that leverages market/economic data to identify early adopters and determine future market projections would help clarify some of these issues.

Commercialization of sCO_2 Brayton cycle technology will depend on various financial, technical, regulatory, social, and value chain factors. These must be properly understood and addressed before commercialization and market risks are alleviated. In order to reduce the risks associated with these factors, it will be essential to support smaller scale projects that mitigate potential risk elements. In addition, as R&D activities advance, the sCO_2 Brayton cycle is expected to achieve higher operating temperatures, allowing for increased potential market opportunities. This progress should be measured on a long-term timescale, with various factors affecting the rate of deployment within given applications. Initial market opportunities for complete systems (offerings from 5 to 10 MWe) will be more clearly understood after concerns about technical risks have been addressed through demonstration.

In the early stages of complete system deployment, the market opportunities are for small (<10 MWe) installations that operate at temperatures below 550°C. Initial applications that meet these criteria include small geothermal facilities or the installation of a sCO_2 Brayton cycle as a bottoming cycle for small (< 100 MW) turbine systems, for both new plants and potentially for retrofit plants. As the technology advances, sCO_2 technology will start to compete with traditional cycles based on expected cost advantages associated with efficiency, capital costs, and operating costs.

The critical point for wide-scale adoption is the demonstration of a system that operates up to 550°C and has addressed technical risks associated with scaling up to higher temperatures. As the technology continues to advance, enabling operational temperatures to increase beyond 700°C, potential market opportunities expand further to include concentrating solar power and fossil fuel direct heating. Over the long-term, as operating temperatures and scalability increase, leading to increased efficiency, the potential market opportunities grow to include large nuclear and fossil fuel plant designs (100 MWe and larger).

Very large market potential exists as technology achieves higher temperatures and efficiencies:

- Total installed capacity in the United States is expected to increase by 196 GW by 2040; however, the projection is for fewer coal plants and for a large increase in natural gas combined cycles (130 GW) and renewables (52 GW).
- Global installed capacity is projected to grow by 3,200 GW by 2040; of that 1,200 GW is expected to be in China. Approximately one-half of this total capacity growth is expected to be gas- or steam-turbine based.
- Dry cooling options are suited for arid regions, including the U.S. southwest, Middle East, and Africa. Successful R&D on dry cooling sCO_2 cycles would increase siting options and may reduce costs associated with water access and rights.

Because sCO_2 power cycles offer advantages across a range of operating temperatures, sCO_2 power cycles are being considered for next generation utility scale fossil fuel power generation, modular nuclear power generation, solar-thermal power generation, geothermal power, and industrial scale waste heat recovery.

Supercritical CO_2 (sCO_2) Power Cycles Summary

Table 4.R.5 describes some of the challenges and desired outcomes for sCO_2 Power Cycles, and Table 4.R.6 summarizes the State-of-the-Art, current R&D activities, and key R&D opportunities for these technologies.

Table 4.R.5 Challenges and Desired Outcomes of sCO_2 Power Cycles

sCO_2 Power Cycles: Perform R&D on both direct and indirect sCO_2 systems, including the development of turbomachinery, recuperators, and syngas oxy-fuel combustors.
Major R&D Challenges ■ Turbomachinery, heat exchanger, and balance-of-plant materials that can withstand 1300°F (700°C) to improve reliability and cycle efficiency ■ Control of kinetics in direct-fired sCO_2 environments with suppression of instabilities and undesired products to improve reliability of the system ■ Identify system design for optimization of performance and cost ■ Develop oxy-combustors for direct cycles to provide a direct-fired system ■ Identify and model control strategies to optimize cycle performance for both indirect and direct-fired systems ■ Integrate fossil energy heat sources for indirect cycles[39] to allow integration with existing firing technologies
Desired Outcomes ■ Pilot testing of a pre-commercial 50 MWe scale sCO_2 power cycle to demonstrate fully integrated, long term, and reliable operation. Specific objectives would be to demonstrate a thermal cycle efficiency (heat in/work out) of 50% or greater, explore long term material performance, demonstrate operational performance (start up, shut down, trips and other transients) and show progress toward a competitive COE for fossil energy, nuclear energy, and concentrating solar applications.

Table 4.R.6 Technical Assessment and Opportunities of sCO_2 Power Cycles

sCO_2 Power Cycles: Perform R&D on both direct and indirect sCO_2 systems, including the development of turbomachinery, recuperators, and syngas oxy-fuel combustors.		
State-of-the-Art	Current R&D	Opportunities and Future Pathways
■ System studies have shown efficiencies higher than USC steam with reduced plant size and simpler operation, suggesting the potential for a COE reduction. Further sCO_2 power cycle and boiler optimization will be required to demonstrate a reduced COE for the sCO_2 power cycle relative to coal based power generation using supercritical steam. ■ Unique system features (e.g., compact turbo machinery), and the potential for lower cost and higher thermodynamic efficiency make sCO_2 power cycles attractive for various heat sources including fossil, nuclear, and solar.[40,41,42] ■ There are sCO_2 power cycle test loops in operation (e.g., Bechtel Marine Propulsion Corp., Sandia National Laboratories, Echogen Power Systems) and other DOE-funded test facilities in planning and/or construction phases.[43,44,45]	■ Materials testing and characterization are being conducted for high temperature and pressure sCO_2 operation. ■ Measurement of thermodynamic (specific heat, density, and conductivity) and transport properties (viscosity) are being conducted to characterize the sCO_2, and identify ideal CO_2-water mixtures (10 – 20%)[46,47] ■ Systems studies are underway to establish optimum cycle operating conditions and boundary conditions for components.[48] ■ Design, construction, and testing of key components, including turbo expanders, compressors, recuperators, and primary heat exchangers, are underway for indirect sCO_2 cycles as well as oxy-combustors for directly heated sCO_2 cycles.[49]	■ Develop components and technologies and scale them to 10MWe size as a next phase of development, and if successful, then to the next scale-up step to a 50 MWe system. ■ Perform component testing and performance evaluation in the 10 MWe pilot test facility, to then be followed by scale-up to 50 MW and higher. ■ Demonstrate cycle and component performance that will lead to large scale, highly efficient cycles.

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Acronyms

Adv	Advanced
ASME	American Society of Mechanical Engineers
AUSC	Advanced ultra-supercritical
BOP	Balance of plant
C	Carbon
Cap	Capture
CCS	Carbon capture and storage

CFB	Circulating fluidized bed
cm	Centimeter, unit of distance
CO_2	Carbon dioxide
COE	Cost of electricity
cp	Heat capacity at constant pressure
CSP	Concentrating solar power
cv	Heat capacity at constant volume
DOE	Department of Energy
EPA	Environmental Protection Agency
Freq	Frequency
GHG	Greenhouse gas
GW	Gigawatt, unit of power
η	Isentropic efficiency
H_2O	Water
He	Helium
K	Kelvin, unit of temperature
kg	Kilogram, unit of mass
kJ	Kilojoule, unit of energy
kJ/kg	Kilojoule per kilogram, unit of specific energy
kPa	Kilopascal, unit of pressure
Lab	Laboratory
lb	Pound, unit of mass
m	Meter, unit of distance
mm	Millimeter, unit of distance
MPa	Megapascal, unit of pressure
MW	Megawatt, unit of power
MWe	Megawatt electrical, unit of electric power
MWh	Megawatt hour, unit of energy
N_2	Nitrogen
nat	Natural
NETL	National Energy Technology Laboratory
NG	Natural gas

Ni	Nickel
O_2	Oxygen
P	Pressure
Pa	Pascal, unit of pressure
P_c	Critical pressure
PC	Pulverized coal
Q	Amount of heat transferred
RB	Recuperated Brayton cycle
RCBC	Recompression CO_2 Brayton cycle
RPM	Revolutions per minute, unit of frequency
R&D	Research and development
SB	Simple Brayton cycle
sCO_2	Supercritical carbon dioxide
SNL	Sandia National Laboratories
syngas	Synthesis gas
T	Temperature
T_c	Critical temperature
USC	Ultra-supercritical
Var	Volt ampere reactive
WHR	Waste heat recovery
°C	Degrees Centigrade, unit of temperature
°F	Degrees Fahrenheit, unit of temperature
$/kW	Dollars per kilowatt, unit of specific cost

Glossary

Advanced ultra-supercritical Rankine cycle	Generally restricted to steam cycles, this is a variant of the supercritical Rankine cycle in which the peak steam temperatures are typically 700-760°C.
Alternator	An electrical generator that converts mechanical energy to electrical energy in the form of alternating current. For reasons of cost and simplicity, most alternators use a rotating magnetic field with a stationary armature.[50]

Axial turbine	A turbine in which the flow of the working fluid is along the axis of the shaft.
Bearing	A machine element that constrains relative motion to only the desired motion, and reduces friction between moving parts.[50]
Brayton cycle	A thermodynamic power cycle for converting thermal energy to power. In an ideal Brayton cycle the working fluid undergoes four steps: isentropic compression, isobaric heating, isentropic expansion, and isobaric cooling. In a real Brayton cycle, the heating and cooling steps entail pressure losses and the compression and expansion steps contain irreversibilities that increase entropy in the working fluid.[51,52]
Brazing	A metal-joining process in which two or more metal items are joined together by melting and flowing a filler metal into the joint, the filler metal having a lower melting point than the adjoining metal.[50]
Carburization	A heat treatment process in which iron or steel absorbs carbon liberated when the metal is heated in the presence of a carbon bearing material, such as charcoal or carbon monoxide, with the intent of making the metal harder.[50]
Creep	Creep is the tendency of a solid material to deform permanently over time under the influence of mechanical stresses at elevated temperatures. It can occur as a result of long-term exposure to high levels of stress that are still below the yield strength of the material.[50]
Critical point	The end point of a phase equilibrium curve. The most prominent example is the liquid-vapor critical point, the end point of the pressure-temperature curve that designates conditions under which a liquid and its vapor can coexist.[50]
Cycle efficiency	The net power generated by a thermal power cycle divided by the thermal energy input to the cycle. Cycle efficiency does not account for balance of plant auxiliary power required by the overall process.
Diffusion-bonding	A solid-state welding technique used in metalworking, capable of joining similar and dissimilar metals. It operates on the principle of solid-state diffusion, wherein the atoms of two solid, metallic surfaces intersperse themselves over time.
Direct-fired	Refers to a thermal power cycle in which heat is added to the working fluid directly by the heat source via combustion of a fuel.
Dry lift off seal	A non-contacting, dry-running mechanical face seal that consists of a mating (rotating) ring and a primary (stationary) ring. When operating, lifting geometry in the rotating ring generates a fluid-dynamic force causing the stationary ring to separate and create a gap between the two rings.[50]

Fatigue	The weakening of a material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading.[50]
Foil	A very thin sheet of metal, usually made by hammering or rolling. Foils are most easily made with malleable metals, such as aluminum, copper, tin, and gold. Foils usually bend under their own weight and can be torn easily.[50]
Gas foil bearing	A shaft is supported by a compliant, spring-loaded foil journal lining. Once the shaft is spinning fast enough, the working fluid pushes the foil away from the shaft so that there is no contact. The shaft and foil are separated by the working fluid's high pressure which is generated by the rotation which pulls gas into the bearing via viscosity effects.[50]
Gearbox	A set of gears with its casing that connects a high-speed shaft (the turbine drive shaft) to a low-speed shaft having the rotational speed required by the generator to produce electricity.[53]
Heat transfer driving force	In a heat exchanger, the driving force that determines the heat flux is the temperature difference between the hot side and the cold side.
Hydrodynamic oil bearing	A type of fluid bearing that relies on the high speed of the journal (the part of the shaft resting on the fluid) to pressurize the oil in a wedge between the faces.[50]
Hydrostatic bearing	Hydrostatic bearings are externally pressurized fluid bearings, where the fluid is usually oil, water, or air, and the pressurization is done by a pump.[50]
Indirect-fired	Refers to a thermal power cycle in which heat is added to the working fluid indirectly by the heat source via heat exchange.
Investment casting	A technique for making small, accurate castings in refractory alloys using a mold formed around a pattern of wax or similar material which is then removed by melting.[54]
Isentropic efficiency	A parameter to measure the degree of degradation of energy in steady-flow devices. For a compressor, the isentropic efficiency is the work required to compress a fluid with no change in entropy divided by the work required to compress a fluid in a real device. For a turbine, the isentropic efficiency is the work generated by the expansion of a fluid in a real device divided by the work generated by the expansion of a fluid with no change in entropy.[55]
Labyrinth seal	A type of mechanical seal that provides a tortuous path to help prevent leakage. An example of such a seal is sometimes found within an axle's bearing to help prevent the leakage of the oil lubricating the bearing.[50]

Magnetic bearing	A bearing that supports a load using magnetic levitation. Magnetic bearings support moving parts without physical contact. Magnetic bearings support the highest speeds of all kinds of bearing and have no maximum relative speed.[50]
Mercury 50	A recuperated gas turbine manufactured by Solar Turbines. It is a product of Solar Turbines' participation in DOE's Advanced Turbine Systems (ATS) program. It features the highest electrical efficiency for a gas turbine in its size range and an ultra-low emissions profile.[56,57]
Oil bearing	A bearing that supports its load solely on a thin layer of oil.[50]
Oxy-fuel	A combustion process in which the oxidant for the fuel is pure or nearly pure oxygen.
Permanent magnet alternator	Also known as a magneto. An electrical generator that uses permanent magnets to produce alternating current. Unlike a dynamo, a magneto does not contain a commutator to produce direct current.[50]
Precipitation strengthened	A process in which closely spaced sub-micron sized particles are distributed throughout an alloy. The particles, which are formed by precipitation, impede dislocation motion through the alloy and thus strengthen it.[58]
Pressure ratio	In the context of a Brayton cycle, the pressure ratio is the maximum pressure of the working fluid in the cycle divided by the minimum pressure of the working fluid in the cycle.
Process efficiency	In the present context refers to the overall efficiency of a power generation facility that contains one or more thermal power cycles. It is equal to the sum of the net power generated by the thermal power cycles minus the balance of plant auxiliary power required by the overall process and is then divided by the thermal energy input to the process.
Radial turbine	A turbine in which the working fluid enters the machine close to its axis and is expanded as it flows radially outwards through the blading.[59]
Rankine cycle	A thermodynamic power cycle for converting thermal energy to power. It is similar to a Brayton cycle except that during the cooling step, the working fluid (most commonly H_2O) condenses to a liquid and is pumped, rather than compressed, to the maximum cycle pressure.
Recompression Brayton cycle	A type of recuperated Brayton cycle in which a portion of the working fluid bypasses the cooler and is recompressed without cooling it first. In supercritical Brayton cycles, recompression improves the effectiveness of the recuperator and improves cycle efficiency.

Recuperated Brayton cycle	A Brayton cycle in which residual thermal energy in the expanded working fluid is used to preheat the working fluid after it has been compressed and before it enters the primary heat source.
Recuperator	In the context of a thermal power cycle, a recuperator is a heat exchanger in which the working fluid exchanges heat with itself. Residual thermal energy remaining in the working fluid after undergoing expansion is used to preheat the working fluid prior to the primary heat source.
Shaft configuration	Refers to the connectivity of shafts with multiple turbomachinery components. In a single shaft configuration, the units share a single shaft and operate at the same rotational speed. In a multi shaft configuration, each unit has a separate shaft.
Slugging	A liquid–gas two-phase flow regime in which the gas phase exists as large bubbles separated by liquid "slugs." Slugging can lead to severe pressure oscillations within piping.[50]
Supercritical fluid	Any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. It can effuse through solids like a gas, and dissolve materials like a liquid.[50]
Supercritical Rankine cycle	A type of Rankine cycle in which the working fluid becomes a supercritical fluid during the cycle. For water, T_c is 374°C and P_c is 22.1 MPa. Typically, supercritical steam plants operate at pressures of 25.5 MPa or higher and temperatures of 565°C or higher.
Synchronous alternator	An alternator in which the waveform of generated voltage is synchronized with (directly corresponds to) the rotor speed. The frequency of output can be given as f = N * P / 120 Hz. where N is speed of the rotor in rpm and P is the number of poles.[50]
Thermal power cycle	A thermodynamic cycle in which a working fluid is heated and then generates power.
Ultra-supercritical Rankine cycle	Generally restricted to steam cycles, this is a variant of the supercritical Rankine cycle in which the peak steam temperatures are typically 600-650°C.
Wound alternator	A type of alternator in which the magnetic field is generated by wound field coils that form an electromagnet.[50]