Power generation from coal using supercritical CO_2 cycle

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

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Abstract

This study describes supercritical carbon dioxide (sCO_2) cycle technologies for power generation from fossil fuels, particularly from coal, and reviews recent developments. The sCO_2 power cycle is an innovative concept for converting thermal energy to electrical energy. It uses sCO_2 as the working fluid in a closed or semi-closed Brayton cycle. These power cycles have several potential benefits, such as high efficiency, small equipment size and plant footprint (and therefore lower capital cost), and the potential for full carbon capture. Achieving the full benefits will depend on overcoming a number of technical, engineering and materials science challenges. Significant progress has been made in developing the systems, with some small, low temperature, sCO_2 Brayton cycles emerging in the commercial market and a natural gas-fired demonstration power plant using a sCO_2 cycle under construction. If this promising technology matures successfully, it could address both energy and environmental challenges and radically change the power generation industry.

Acronyms and abbreviations

ACFB	atmospheric circulating fluidised bed
AGR	acid gas removal
ANL	Argonne National Laboratory (USA)
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASU	air separation unit
BMPC	Bechtel Marine Propulsion Corporation
CB&I	Chicago Bridge & Iron Company
CCS	carbon capture and storage
CES	Clean Energy Systems
CFB	circulating fluidised bed
CFD	computational fluid dynamics
CGE	cold gas efficiency
CHE	compact heat exchanger
CMHE	cast metal heat exchanger
COE	cost of electricity
COS	carbonyl sulphide
CPOC	Cryogenic Pressurized Oxy-Combustion Cycle
CRADA	Cooperative Research and Development Agreement
CSP	concentrating solar power
DCC	direct contact cooler
EDF	Électricité de France
EERE	Office of Energy Efficiency and Renewable Energy (USA)
EGS	enhanced geothermal system
EPRI	Electric Power Research Institute (USA)
FEED	front end engineering design
GE	General Electric
GHG	greenhouse gas
GTI	Gas Technology Institute (USA)
HE	heat exchanger
HELC	high effectiveness low cost
HHV	high heating value
HPT	high-pressure turbine
HTF	heat transfer fluid
IEAGHG	IEA Greenhouse Gas R&D Programme
IGCC	integrated gasification combined cycle
KAERI	Korea Atomic Energy Research Institute
KAIST	Korea Advanced Institute of Science & Technology
KIER	Korea Institute of Energy Research
LCOE	levelised cost of electricity
LHV	low heating value
LOX	liquid oxygen
LPT	low-pressure turbine
MWe	megawatt electricity
MWth	megawatt thermal
NAL	Argonne National Laboratory (USA)
NETL	National Energy Technology Laboratory (USA)

NGCC	natural gas-fired combined cycle
NREL	National Renewable Energy Laboratory (USA)
ORNL	Oak Ridge National Laboratory (USA)
PC	pulverised coal
PFB	pressurised fluidised bed
PCHE	printed circuit heat exchangers
PDC	plant dynamics code
POSTECH	Pohang University of Science and Technology (South Korea)
R&D	research and development
RDD&D	research, development, demonstration and deployment
rpm	revolutions per minute
SCOC-CC	semi-closed oxy-combustion combined cycle
SCPC	supercritical pulverised coal
sCO_2	supercritical carbon dioxide
SNL	Sandia National Laboratories (USA)
SWRI	Southwest Research Institute (USA)
TIT	turbine inlet temperature
TITech	Tokyo Institute of Technology (Japan)
US DOE	United States Department of Energy
USC	ultrasupercritical
VPE	Vacuum Process Engineering (USA)

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1 Introduction

Since before the start of this century, increasing political and technological focus has been given to minimising emissions of carbon dioxide (CO_2), a greenhouse gas, in order to control climate change. The Paris Agreement adopted at the COP21 Conference, which entered into force on 4 November 2016, aims to cap global warming at well below 2°C (1.5°C if possible), compared with pre-industrial levels, and to reach a global peak of greenhouse gas (GHG) emissions as soon as possible. To meet these goals, each Party to the Agreement needs to set an ambitious national GHG emissions reduction target and to take concrete measures to ensure the target is met.

A significant source of CO_2 entering the atmosphere is from combustion of coal to generate electric power. Coal currently supplies ~40% of global electricity and will remain a major energy source for the foreseeable future, so further improving efficiency, emissions control and costs remain vital. Recently, the development of high efficiency, low emissions (HELE) coal power generation technologies has achieved major progress and carbon capture and storage (CCS) could also substantially reduce CO_2 emissions. The International Energy Agency (IEA, 2016) projects that to control global temperature rise to less than 2°C, CCS will be required for 12% of the global cumulative CO_2 emissions reductions by 2050. The United Nations Framework Convention on Climate Change estimates that, without CCS, the costs of achieving this global goal would increase by 138% (IPCC, 2014). However, the employment of CCS comes with significant cost and efficiency penalties.

There have been extensive research and development (R&D) activities to improve plant costs and overall efficiencies. Alternative combustion processes and/or power cycles are also being explored. For coal-fired power plants, these technologies include advanced turbines, oxyfuel combustion, supercritical CO_2 (sCO_2) power cycles, and high-temperature durable materials.

The sCO_2 power cycle uses supercritical CO_2 as the working fluid in a Brayton thermodynamic cycle (basically, the cycle exploited in a gas turbine). Results from a number of studies have shown that these systems have the potential to achieve higher efficiencies than steam cycles operating between the same maximum and minimum temperatures. For coal-fired power plants, higher efficiency results in lower emissions of all types, including CO_2. The high density of the working fluid will also lead to smaller equipment, and so reduced capital and operating costs. Furthermore, semi-closed, oxyfuel combustion sCO_2 power cycles, that will burn clean gaseous fuel directly within the gas stream, have the additional bonus of facilitating CO_2 capture.

To develop commercial sCO_2 cycles that are technically viable and economically competitive, a number of technical, engineering and materials science challenges need to be tackled. This study investigates the current states of research, development, demonstration and deployment (RDD&D) of sCO_2 cycles with a focus on the sCO_2 cycles for fossil fuel, in particular, coal power. It begins with a brief introduction to sCO_2 Brayton cycles in Chapter 2. The main benefits and potential applications of sCO_2 power cycles are also described. The technical challenges and R&D needs for developing utility-scale commercial power conversion systems using sCO_2 cycles are discussed in Chapter 3. The recent, extensive RD&D particularly in the USA, that addresses these issues is reviewed in Chapter 4. Several variations to a closed loop, simple sCO_2 Brayton cycle have been proposed and analysed for coal power plants. Chapter 5 describes developments in power cycles using sCO_2, including some performance and economic assessments. It also describes first examples of commercialisation of the technology. Summary and conclusions are in Chapter 6.

2 Supercritical CO_2 power cycles

2.1 CO_2 as a working fluid

A supercritical fluid describes any substance at a temperature and pressure above its critical point, where liquid and gas phases are not distinguishable. Supercritical CO_2 has many properties that make it an ideal working fluid. CO_2 is non-explosive, non-flammable, non-toxic and readily available at low cost. Small changes in temperature near its critical point cause changes in density, similar to boiling where a liquid changes to a vapour. The density change, however, is only by a factor of three or four, not a thousand, as when water becomes steam at atmospheric pressure. It takes considerable energy to increase the temperature a small amount when the fluid is near the critical point, much the way the heat of vaporisation requires energy to convert a liquid to a vapour. Consequently, a large spike in heat capacity occurs near the critical point. These properties make sCO_2 an attractive working fluid for Brayton cycles.

The sCO_2 cycle operates in a single phase with no condensation occurring. CO_2 has a relatively low critical pressure and critical temperature: 7.4 MPa and 31°C, respectively. A consequence of this is that it can be compressed directly to supercritical pressures and readily heated to a supercritical state before expansion. In a heat engine, this can facilitate obtaining a good thermal match with the heat source. The critical temperature is also sufficiently high for ready heat rejection from the cycle at terrestrial ambient temperatures. Therefore, the system has a great potential for high efficiency since a large temperature difference is available. CO_2 near its critical point becomes more incompressible and hence, the compression work can be substantially decreased leading to high cycle efficiency. Also, in its supercritical state, CO_2 is nearly twice as dense as steam. The high density and volumetric heat capacity of sCO_2 with respect to other working fluids make it more energy dense meaning that the size of most system components such as turbine and pump can be considerably reduced which leads to a smaller plant footprint and possibly lower capital costs.

2.2 Supercritical CO_2 power cycles

While there has been increasing interest recently, the idea of using sCO_2 in a power system is not new. A patent for a partial condensation CO_2 Brayton cycle was submitted by Sulzer Bros in Switzerland in 1948. The principle was reinvented two decades later and work by Angelino (1969) showed that for a cooling water temperature of 5°C and turbine inlet temperature of 700°C, a cycle efficiency in excess of 50% was achievable, which was better than that of a double reheat steam cycle at the same maximum temperature. Dostal and others (2004) studied the use of sCO_2 in Brayton cycle turbines for nuclear power, and this work led to research worldwide and the development of sCO_2 power cycles.

Later, approximately 10 years ago, Sandia National Laboratories (SNL) based in the USA, began to investigate the sCO_2 power cycle as part of the US Department of Energy (DOE) GenIV Program on advanced nuclear reactors. SNL operated a small-scale sCO_2 compression loop, opened in May 2008. Positive results led to the construction of a 240 kWe simple recuperated test loop in 2012, one of the first sCO_2 power producing cycles operating in the world – the compression and recuperated terms are explained later in this chapter. Further information on SNL's work and follow-on developments appears in Chapter 4. The remainder of this chapter concentrates on the principles of sCO_2 systems.

Two primary approaches to electricity generation power cycles using sCO_2 as the working fluid have been investigated: indirectly-heated (or indirectly fired) cycles and directly-fired cycles. There are then variants of each, described in the following sections.

2.2.1 Indirectly-fired closed-loop sCO_2 Brayton cycles

A closed-loop, indirectly-fired sCO_2 Brayton cycle is applicable to most thermal energy sources, such as fossil fuel combustion, nuclear, solar, geothermal and waste heat recovery.

Simple closed-loop Brayton cycle

Figure 1 shows a diagram of a simple closed-loop Brayton cycle. CO_2 (the working fluid) is heated indirectly from a heat source through a heat exchanger (heater), similar to the way steam would be heated in a conventional boiler. Energy is extracted from the CO_2 as it is expanded in the turbine. The CO_2 exiting the turbine is then cooled in a heat exchanger (cooler) to the desired compressor inlet temperature. After compression to the required pressure, the CO_2 is sent back to the heater to complete the cycle. The cycle efficiency is a function of the ratio of turbine inlet and exit pressure and turbine inlet temperature (TIT). The efficiency of the CO_2 closed cycle is strongly dependent on the minimum pressure in the cycle. At an arbitrary TIT of 700°C, a maximum cycle efficiency of 34.5% is achieved by this simple sCO_2 Brayton cycle at the turbine exit pressure of approximately 8.27 MPa (US DOE, 2015).

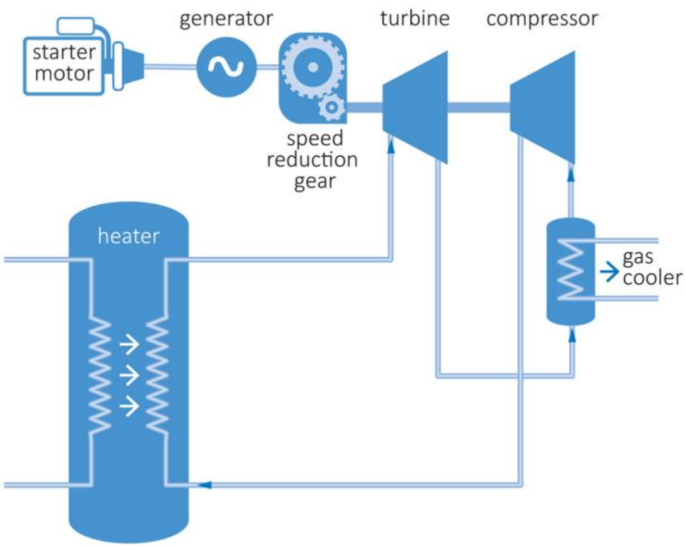


Figure 1 A simple indirectly-fired, closed-loop Brayton cycle (US DOE, 2015)

Recuperated closed-loop Brayton cycle

A more advanced version of the indirectly-fired Brayton cycle incorporates thermal recuperation. In a recuperated, closed cycle, a heat exchanger(s) is introduced between the expander (turbine) exhaust and the compressor exhaust (*see* Figure 2). Introducing a recuperator in the cycle, in which a portion of the sensible heat in the turbine exhaust is used to preheat the working fluid prior to entering the heat source, improves the cycle efficiency by reducing the amount of heat loss in the CO_2 cooler. Recuperation reduces the high temperature heat duty and allows a greater flow of working fluid in the cycle, leading to a higher efficiency than the corresponding simple cycle over the entire range of feasible pressure ratios. A disadvantage to this approach is that, as the heat capacity of CO_2 increases significantly with increasing pressure near the CO_2 critical point (*see* Section 2.1), operating the cycle at pressures in this region will cause the recuperation efficiency to be reduced, limiting the temperature of the high pressure CO_2 that leaves the recuperator. This is because, under these conditions, the heat capacity of the hot CO_2 on the low-pressure side of the recuperator is much lower than that of the cold CO_2 on the high-pressure side of the recuperator. This will reduce cycle efficiency. One approach to overcome this problem is to add a recompressor into the cycle.

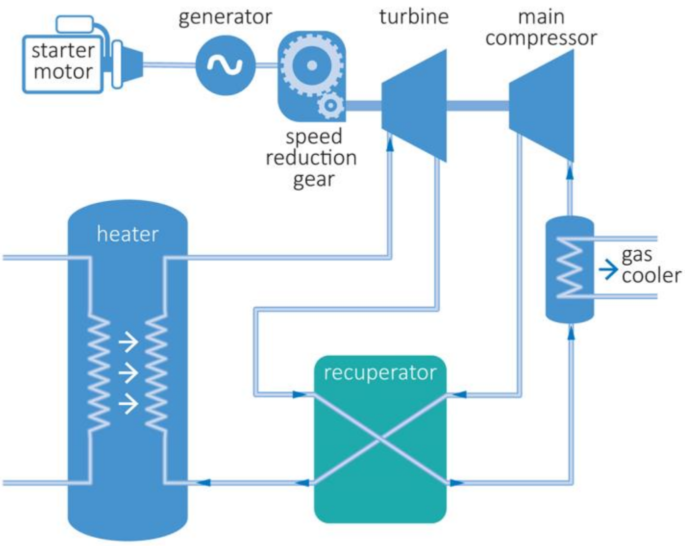


Figure 2 An indirectly-fired, recuperated, closed Brayton cycle (US DOE, 2015)

Recuperated recompression closed-loop Brayton cycle

Figure 3 shows a diagram of an indirectly-heated, recuperated, recompression sCO_2 Brayton cycle. Points C–H in Figure 3 are the same as for the recuperated cycle shown in Figure 2. The differences between the recompression and recuperated cycle lie downstream of point H. In the recompression cycle configuration, the low-pressure CO_2 stream exiting the recuperator is split into two. One portion is cooled in the CO_2 cooler and is then compressed in the main compressor before being heated in the low-temperature recuperator. The other stream bypasses the CO_2 cooler and is compressed in the re-compressor to the maximum cycle pressure. It is then mixed with the stream exiting the low-temperature recuperator and the mixture passes through a high-temperature recuperator and the CO_2 heater. With this cycle layout, the heat capacity between the hot and cold sides of the recuperator is better matched and hence, the overall efficiency of the recuperator is improved. However, this configuration is more complex and may have higher costs due to requiring an extra compressor. The net cycle efficiency is higher in this configuration although the total amount of power required for CO_2 compression actually increases. At the optimal pressure ratio for maximum cycle efficiency, the efficiency of the recompression cycle is over 5% points higher than that of the recuperated cycle (US DOE, 2015).

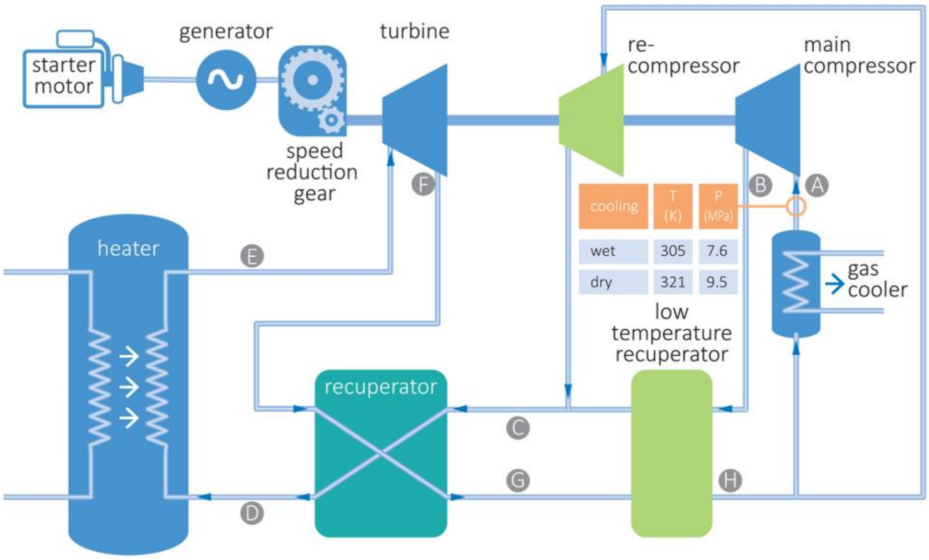


Figure 3 An indirectly-fired, recuperated, recompression, closed Brayton cycle (US DOE, 2015)

There are many other variations of indirectly-fired sCO_2 power cycles using different compression, reheating and other cycle configurations such as pre-compression, intercooling and split expansion, to increase the efficiency of the cycle or to adapt to particular applications. Ahn and others (2015) recently reviewed and analysed various configurations. Their results indicate that the recompression Brayton cycle has the best efficiency. This finding is consistent with the results of an earlier study on thermodynamic analysis and comparison of various sCO_2 cycles (Kulhánek and Dostal, 2009).

2.2.2 Directly-fired, semi-closed oxyfuel Brayton cycle

A diagram of a simplified semi-closed, directly-fired, oxyfuel sCO_2 cycle is shown in Figure 4. Here, the CO_2 heater is replaced with a pressurised oxyfuel combustor. Fuel is burned in relatively pure and near-stoichiometric oxygen in the combustor, and the resulting stream, which contains mainly CO_2 and H_2O, is used to drive the turbine. The remaining heat in the stream exiting the turbine is recuperated and the stream is then further cooled to condense the water out, leaving a stream of high concentration CO_2. A portion of the CO_2 is compressed to the desired pressure. The cooled and compressed CO_2 passes through the recuperator to be preheated and it is then recycled to the combustor as diluent. The remainder of the CO_2 is ready to be compressed for storage.

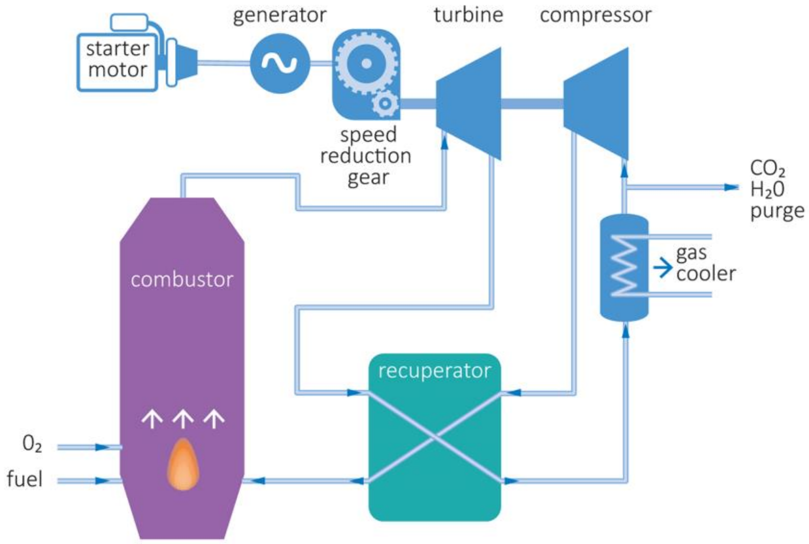


Figure 4 A simplified directly-fired, semi-closed, oxyfuel Brayton cycle (US DOE, 2015)

Semi-closed, directly-fired, oxyfuel sCO_2 cycles are well-suited to oxy-combustion of gaseous fuels such as natural gas and syngas derived from coal gasification, in particular when carbon capture is required. Due to the fact that a much higher TIT can be attained in a directly-fired sCO_2 cycle, cycle efficiencies have the potential to be significantly higher than those of the indirectly-heated closed cycles. The cycle configuration may be simpler since recompression and other measures for maximising the cycle efficiency are not needed.

2.3 sCO_2 in power generation applications

An indirectly-heated closed Brayton cycle can replace a Rankine cycle. Moreover, its low critical pressure and temperature mean that a better thermal match can be achieved over a wide temperature range. This will allow both topping and bottoming cycles to be applied. The most promising application areas for directly-fired, semi-closed sCO_2 cycles are in natural gas- or syngas-fired power generation. Table 1 summarises the potential application areas and benefits of these systems.

Table 1 Potential applications for sCO_2 for power conversion (US DOE, 2015)

Application	Cycle type	Benefits	Size, MWe	Temperature, °C	Pressure, MPa
Nuclear	Indirect sCO_2	Efficiency, size, water reduction	10–300	350–700	20–35
Fossil fuel (such as PC, CFB)	Indirect sCO_2	Efficiency, water reduction	300–600	550–760*	15–35
Concentrating solar power	Indirect sCO_2	Efficiency, size, water reduction	10–100	500–700*	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, natural gas)	Direct sCO_2	Efficiency, water reduction, CO_2 capture	300–600	1100–1300*	35

∗ numbers modified from the original figures

Future indirectly-heated cycles for coal may use pulverised combustion (PC) or circulating fluidised bed (CFB) combustion, while directly-fired systems would use synthesis gas (syngas) from coal gasification. Both approaches have the potential to significantly increase efficiency and reduce the cost of electricity. A semi-closed directly-fired oxy-combustion cycle would reach high plant efficiency while achieving full carbon capture. In the case of the indirectly-heated closed sCO_2 cycle, the increase in efficiency would effectively compensate for the loss of energy used for CCS.

The use of sCO_2 in power turbines has been an active area of research for a number of years but earlier work was mostly dedicated to its application in nuclear power. Currently, the sCO_2 power cycle is being considered for solar, advanced fossil and other energy sources. Several projects are underway to develop sCO_2 power systems for fossil fuel power applications. Significant progress has been made and this is discussed in Chapters 4 and 5.

2.4 Main benefits

The principal benefit of the sCO_2 power cycle is the high thermal efficiency at moderate temperatures due to the small compression work and large amount of heat in the turbine exhaust that is recuperated and turned into power. The high-power density of sCO_2 means all system components are much smaller, leading to a reduced plant footprint and potentially lower capital costs. The low-pressure ratio of the turbine reduces the number of stages required. Recompression, expansion and heat rejection are carried out in a single phase, reducing the complexity of the system. Lower operation and maintenance costs for sCO_2 power cycles are possible because plant personnel will not be needed for water treatment and quality control that are typically found in steam-based power plants. Another potential benefit is the compatibility of the sCO_2 cycle with dry cooling due to the relatively high heat rejection temperature. This could make the sCO_2 cycle more practical than the steam cycle in locations where water is scarce.

Summary

The sCO_2 Brayton cycle is an innovative energy conversion system that converts heat energy to electrical energy, using sCO_2 as the working fluid. CO_2 has thermodynamic properties that support efficient cycles – up to 50% or greater. The high energy density of sCO_2 means that the components and overall plant footprint will be smaller. These attributes, together with the simple layout of sCO_2 power cycles could result in large potential reductions in capital and fuel costs and decreased GHG emissions from coal-fired power generation. In order to implement sCO_2 cycles using coal as fuel, the cycle would either be indirectly heated in a boiler, akin to a steam raising system, or the coal would have to be converted to clean syngas, then the latter directly fired in a supercritical turbine-combustor.

3 Technical challenges

3.1 Current technology readiness

In general, components such as the generator, heat rejection subsystem, plant control systems and instrumentation are mature technologies as they are already in commercial operation in power plants and industrial processes. Although the development of control methods and design optimisation of these components for a given application may be required, it can be assumed that the performance, reliability and cost of these components are reasonably predictable and they do not present any major risk or obstacle to the commercial deployment of sCO_2 power cycles. In addition, equipment for compressing and pumping sCO_2 are already used in the oil and gas industry for other applications, and so the compression technology required for the sCO_2 cycle is considered mature and presents little risk. However, several parts of the sCO_2 cycle still require significant R&D.

3.2 R&D needs

3.2.1 Turbomachinery

The fundamentals of, and engineering tools for, conventional turbine and compressor designs are mature. However, there is limited operational experience of sCO_2 power turbines. In addition to high density and high pressure, the properties of CO_2 such as density and viscosity change rapidly near the critical point. Particular challenges include the design of reliable seals and bearings, and identifying materials and coating technologies that are compatible with high temperature, high pressure operation in a sCO_2 environment. For directly-fired semi-closed oxy-combustion cycles, achieving a high turbine inlet temperature is limited by the maximum allowable temperature of the turbine exhaust that flows directly into the recuperator that would be needed in practical systems. For the Allam Cycle under development by 8 Rivers Capital (USA), the operating temperature at the hot end of the recuperator, typically in the range 700–750°C, leads to a typical turbine inlet temperature specification of 1100–1200°C.

To achieve high efficiency, it is essential to optimise the design and engineering of the turbine and compressor. Conceptual designs need to be validated by engineering and thermodynamic analyses and small-scale turbines and compressors need to be built for verification. The scale for testing has to be carefully selected to simplify turbomachinery scale-up. Figure 5 illustrates development stages for major system components at different scales. Laboratory- and pilot-scale sCO_2 cycle test loops with varying sCO_2 turbine capacities have been assembled and used as test beds in Japan, South Korea, USA and other countries.

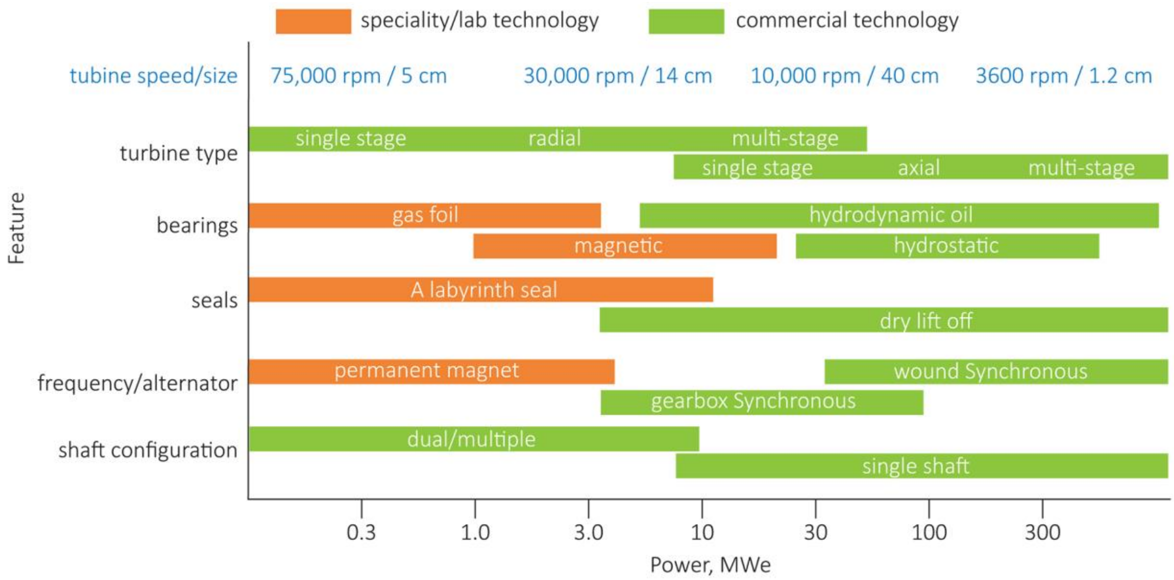


Figure 5 Ranges of application for key Brayton cycle turbomachinery components and features (Turchi, 2014)

3.2.2 Recuperators

One of the major technical challenges in the development of sCO_2 power cycles is the design of low-cost and compact recuperators. Recuperators are key to delivering higher cycle efficiency but are expensive. The detailed heat transfer mechanisms of sCO_2 are not well understood. For both directly- and indirectly-fired sCO_2 cycles, the recuperators need to operate at high temperatures (in excess of 700°C) and high pressures (as high as 30 MPa) as well as high pressure differentials between the cold and hot side. A major challenge is to design a heat exchanger with minimal pressure drop across the system while pursuing effective heat transfer. The heavy heat duty of recuperation requires a large heat transfer surface area. Conventional shell and tube heat exchangers are not practical for this because their relatively low surface area to volume ratio (<100 m^2/m^3) would lead to massive and expensive heat exchangers. Compact heat exchangers (CHE), such as printed circuit and plate-fin heat exchangers, have a high surface area to volume ratio (typically >700 m^2/m^3) and are good candidates. Significant progress in developing CHE has been made recently and some are now in commercial operation in the chemical and gas industry. However, more robust and cost-effective CHE are needed for application in commercial sCO_2 power cycles. In addition, innovative metallurgical and fabrication processes need to be developed to address diffusion-bonding and metal casting techniques, and to reduce the costs. For directly-fired sCO_2 cycles, specific issues such as corrosion due to the presence of water and other contaminants resulting from fossil fuel combustion will also need to be addressed. As the recuperator costs could prove to be a limiting factor in commercialising the sCO_2 cycle power system, the challenge remains to find the optimal cycle design which balances increased efficiency and increased costs, as added recuperation to increase the system efficiency will substantially increase the cost (Strakey and others, 2014; US DOE, 2015).

3.2.3 Combustor and CO_2 heater

The difficulties in designing a sCO_2 heater for indirectly-heated cycles depend on the given application and heat source, in particular, the temperature profile of the heat source. CO_2 heaters for indirectly-heated sCO_2 cycles for coal power generation have many similarities to existing steam boilers, as explained in Section 2.2.1. For example, the working fluid is indirectly heated in a boiler and circulated in a closed cycle. However, the specific heat capacity of CO_2 is much lower than that of water. The average driving force for heat transfer (the temperature difference between the hot side and cold side) can also be much lower. Therefore, a greater heat transfer area is required, making designing a sCO_2 heater challenging. The challenges in designing the final stage of heating the CO_2 before it enters the turbine are similar to those of recuperators, for example, minimising pressure drop.

The heat source temperature profile will be broad with indirect fossil-fuelled combustors and bottoming cycle applications. The optimum sCO_2 cycle configuration that can effectively recover sensible heat from the flue gas needs to be developed to maintain high system efficiency.

Another challenge is the need for air preheaters with higher flue gas inlet and higher air outlet temperatures, which is necessary to achieve high overall thermal efficiency. Indirectly-fired cycles will require air preheaters with different boundary conditions from those on conventional power plants, with higher flue gas inlet and higher air outlet temperatures necessary to achieve high overall thermal efficiency. The large amount of recuperation of CO_2 means the temperature of the CO_2 entering the fired heater is higher than the boiler feedwater entering a coal boiler. A consequence of this is that the flue gas exit temperature from a sCO_2 heater will be higher than it is from a coal boiler (Phillips, 2017).

A directly-fired sCO_2 combustor resembles a conventional gas turbine combustor. The upper temperature will generally be lower than in existing heavy frame gas turbines, while the pressure will be higher. With pressures in the order of 30 MPa and high energy densities, issues such as injector design, wall heat transfer and combustion dynamics will play a challenging role in combustor design, of which there is little experience.

Perhaps a more significant challenge is designing the oxy-combustor for high pressure operation with a minimum amount of excess oxygen and a large amount of recycled CO_2 diluent. Oxy-combustor operation at pressures higher than 20 MPa poses a significant technical risk as high oxy-combustor inlet temperatures enable auto-ignition. The design also needs to address the issue of soot formation, especially for a natural gas fired oxy-combustor with minimal excess oxygen although it may be less of a problem for syngas fired oxy-combustion. The reaction kinetics and mechanism at high temperature and pressure are not understood and the radiant effects of heat are uncertain. Tests and computer modelling are needed to develop oxy-combustor designs for natural gas and syngas (from coal gasification) that ensure complete combustion and minimise hot spots and wall temperatures in the combustor (US DOE, 2015; McClung, 2015; Phillips, 2017).

3.2.4 Materials

Materials selection for components such as turbines and heat exchangers is challenging. The temperature and pressure can be up to 760°C and 30 MPa, respectively, for indirectly-heated, closed sCO_2 power cycles and 1150°C and 30 MPa for directly-fired, semi-closed sCO_2 power cycles. Uncertainties about materials reliability include carburisation and sensitisation, high-temperature corrosion, erosion, creep and thermal fatigue. Previous studies have shown internal carburisation of conventional austenitic steels in CO_2 environments in a temperature range of 480–650°C. Similar carburisation of ferritic-martensitic steels also had been observed at 550–650°C (Garrett and others, 1982; Tan and others, 2011; Moore and Conboy, 2012). If these less expensive ferritic-martensitic and austenitic steels are to be used, R&D is needed on the long-term carburisation behaviour and maximum use temperature of these alloys to identify degradation mechanisms and to predict the useful life.

While pure, dry CO_2 is virtually inert at temperatures of <500°C, corrosion of steels and nickel alloys can occur when exposed to sCO_2 at high temperatures (>600°C), particularly in the presence of even small quantities of water and other contaminants. Materials for advanced ultrasupercritical steam cycles are designed to withstand high temperatures. However, for sCO_2 applications, the oxidation reaction kinetics and the rate of internal carburisation of alloy candidates over 1000-5000 hours in sCO_2 at high pressures (20–35 MPa) and high temperatures (650–750°C) needs to be established. Furthermore, the long-term effect on various joining techniques such as diffusion bonding and brazing on degradation rates needs to be determined. For the directly-fired, semi-closed sCO_2 cycles, impurities may affect corrosion rates so oxidation and corrosion data for these conditions are needed (Wright and others, 2013).

sCO_2 is more dense than supercritical steam under the same temperature and pressure conditions and the required mass flow rate will be much greater than it is in steam systems. As a result, sCO_2 cycles will experience high density fluid flow rates at high velocities. Therefore, even a tiny amount of particles present in the sCO_2 stream could cause substantial erosion to turbine components. In closed sCO_2 cycle tests, erosion has been observed that is believed to be caused by residual debris in the loop and/or small particulates formed by corrosion reactions of materials. For semi-closed sCO_2 cycles in syngas applications, the efficient removal of fine particulates from syngas needs to be addressed. It may be possible to select coating systems from those used for gas and steam turbine protection, but work is needed to confirm this.

Creep and fatigue of materials are potentially the major limitations to the lifetime of sCO_2 turbomachinery and heat exchangers. R&D is needed to better understand the processes under sCO_2 cycle operational conditions. The creep and fatigue behaviour of joints (diffusion bonded or brazed) also needs to be evaluated as a part of the development of compact heat exchanger designs. In addition, the effects of the operating environment, for example, carburisation and oxidation of alloys, on the creep rate and fatigue crack growth rate need determining (US DOE, 2015; Fleming and others, 2014a).

3.2.5 System integration

System integration is important to optimise cycles and to address issues of start-up, shut-down, and transient and part-load operation. The system design should allow for pressure containment in, and the minimum leakage of, the system as well as mechanical stability. Dynamic processes within the system such as pressure surging, heat transfer and convection, turbulent flow conditions, pressure waves and acoustics must be considered for integrated plant operation. The sCO_2 power systems should have operational flexibilities such as wide turn-down capability and quick response to changes in demand. The effects of impurities in the sCO_2 working fluid, for example, CO, H_2O and the formation of H_2CO_3, should also be taken into account (US DOE, 2015).

3.2.6 Other R&D needs

Specialised approaches are required to develop subcomponents such as turbine and compressor shafts, bearings, seals, valves and alternators to achieve scale up of turbomachinery from small laboratory scale to multi-MW size. Many different technologies are commercially available and may be considered for use in sCO_2 cycles. However, utility-scale component designs need to be tested to validate performance. Other R&D needs include piping design and new control methods. Fundamental studies and computer modelling are also needed to understand the properties of CO_2 in near-supercritical conditions as well as combustion kinetics at high temperature, high pressure conditions in the presence of CO_2 diluent. High quality thermo-physical property data of CO_2 are essential for accurate simulation of sCO_2 power cycles and individual components such as recuperators. The REFPROP physical property method, developed by the US National Institute of Standards and Technology (www.nist.gov/srd/refprop), in which the Span-Wagner equation of state (EOS) is incorporated, can provide accurate quantitative predictions of physical properties of process streams consisting of pure CO_2 over a wide temperature and pressure range. It has been used by most researchers in modelling indirectly-heated sCO_2 power cycles. However, for directly-fired, semi-closed oxy-combustion sCO_2 cycles, the working fluid is not pure CO_2. Also, the composition of the working fluid changes at various points in the cycle. Using REFPROP on such process streams will generate significant errors. Recently, White and Weiland (2017) quantitatively evaluated ten different physical property methods for use in modelling coal derived syngas-fired, oxy-combustion semi-closed sCO_2 cycles using Aspen Plus. Their work showed that different methods all had limitations in accurately modelling fluid properties for directly-fired oxy-combustion sCO_2 power systems under operating conditions. More work is needed to develop models that can accurately predict working fluid properties for directly-fired oxy-combustion sCO_2 cycles. In addition, extensive experimental data are needed for model validation. System modelling and analyses are also necessary to identify cycle conditions for optimised cycle performance, cost and operability, and to translate cycle efficiency benefits to plant efficiency improvement.

Recently, Dawson and Carlson (2016) reviewed sCO_2 cycle testing philosophy and proposed a pathway for R&D of sCO_2 power cycle technology from laboratory tests to commercialisation. They identified that corrosion, turbine erosion, turbine control, thrust management and seals were the highest technical risks which must be solved before an integrated prototype can be demonstrated at commercial scale in a relevant environment.

In summary, the main challenges of developing sCO_2 power systems arise from the very factors that lead to a higher cycle efficiency. These factors include: elevated pressures throughout the cycle; a large duty heat exchanger as well as materials compatible with operation at high pressure and temperature in sCO_2 and thermal integration and optimisation at cycle and process level. In particular, R&D is required for:

- **CO_2 turbines –** design development and performance validation, material selection, cooling and coating methods for high temperature operation and corrosion and erosion resistance, tests of key subcomponents for sealing and thrust management, for example;
- **recuperators –** developing and optimising designs for high efficiency and robust CHE with minimum pressure drop, materials testing and innovative fabrication processes for durable and low-cost recuperators;
- **combustors –** design and tests of oxy-combustor for high pressure operation;
- **materials –** tests to identify materials compatible for operation in various parts within a sCO_2 cycle that may endure high temperature, high pressure and high differential pressure under sCO_2 cycle operation conditions and in a sCO_2 environment;
- **cycle configuration –** identify optimised sCO_2 power cycle layout for a given application; and
- **computer models -** assessment of performance and cost of the sCO_2 cycles and individual components.

4 Recent developments

4.1 R&D activities

Chapter 2 included a brief summary of the history of the technology, finishing with reference to SNL's work on sCO_2 power systems. SNL (Sandia National Laboratories) has two operating experimental sCO_2 loops as part of ongoing work to determine the feasibility of the technology. SNL contracted Barber Nichols Incorporated to construct a small-scale sCO_2 compression loop, completed in May 2008. Investigations of compressor performance and stability and of issues with compression, bearings, and seals near the critical point of CO_2 were carried out. A 240 kWe recuperated test loop followed in 2012, one of the first sCO_2 power producing cycles operating in the world. As well as turbomachinery, printed circuit heat exchangers (PCHE), manufactured by Heatric in the UK were tested. PCHEs are described in Section 4.2.2. Test results of high power density heat exchanger performance proved positive and system start-up protocols and system controllability were established. In addition, SNL developed computational models to analyse cycles. Material corrosion and erosion behaviours in sCO_2 power cycles were also investigated (Wright, 2012; Lewis and Rochau, 2012; Wright and others, 2010). Since 2012, SNL has been working with other partners to develop large (>10 MWe) sCO_2 cycle units for various electrical production schemes. Another 100 kWe Integrated System Test (IST) facility was built at the Bettis Atomic Power Laboratory (USA) to demonstrate the operation of an sCO_2 power cycle over a range of conditions. This was operated at a turbine inlet temperature of 299°C. During tests since 2012, load control by independent speed control of the turbomachinery and steady-state operation at up to 40 kWe have been achieved and a dynamic performance model has been developed (Kimball, 2014; Clementoni and Cox, 2014; Clementoni and others, 2016).

In 2014, the US DOE National Energy Technology Laboratory (NETL) funded a number of projects to further develop sCO_2 power cycles. The objective of the 'Turbomachinery components for supercritical CO_2 power cycles programme' was to develop innovative turbomachinery components for sCO_2 cycles for fossil fuels with plant efficiencies (with CCS) >52%. The project participants include Aerojet Rocketdyne (USA), the Electric Power Research Institute (EPRI), Duke Energy (USA), Alstom and Oak Ridge National Laboratory (ORNL). Various configurations for an indirectly-heated closed-loop Brayton cycle and a directly-fired oxy-combustion sCO_2 cycle were investigated. 'High-efficiency thermal integration of closed supercritical CO_2 Brayton power cycles with oxyfired heaters' was simulated in comparison with other advanced power generation technologies. Another project, the 'Development of low-leakage shaft end seals for utility-scale sCO_2 turbomachinery' was awarded to General Electric (GE) to develop turbine shaft end seals of leakage less than 0.2%. Southwest Research Institute (SWRI), in partnership with Thar Energy LLC and Knolls Atomic Power Laboratory were involved in R&D of 'High inlet temperature combustor for directly fired supercritical oxy-combustion power plant'. Thar Energy LLC and SWRI also worked on developing 'High temperature heat exchange design and fabrication for systems with large pressure differentials' and operation at high temperature. In addition, several US universities and companies such as Oregon State University, Carnegie Mellon University, Babcock & Wilcox Power Generation Group, Echogen Power

Systems, Dresser-Rand and Brayton Energy LLC were contracted by US DOE to develop high-performance, low-cost recuperative heat exchangers (Dennis, 2014).

In July 2016, the US DOE announced that it would invest a further US$30 million in projects developing components for advanced turbine and sCO_2-based cycles. NETL selected 'Development of low-leakage seals for utility-scale sCO_2 turbines' and 'High-inlet temperature combustor for directly-fired supercritical oxy-combustion' as Phase II projects for sCO_2 cycles. The former aims to develop turbine end and inter-stage seals for a utility-scale field-trial-ready design. It is being carried out by GE Global Research (USA), in partnership with SWRI. The objective of the latter is to demonstrate a sCO_2 oxy-combustor for a state-of-the-art fossil-fired sCO_2 power cycle and is being carried out by SWRI (USA), in partnership with Thar Energy LLC, GE Global Research, Georgia Institute of Technology and the University of Central Florida of USA. In October 2016, the US DOE announced they would award up to US$80 million for a six-year project to design, build, and operate a 10 MWe sCO_2 pilot plant facility. The project will be managed by a team led by the Gas Technology Institute (GTI), SWRI and GE Global Research. GTI will design, build, commission, and operate the sCO_2 pilot facility located at SWRI's campus in San Antonio, Texas, USA (https://energy.gov/).

In parallel to sponsoring the R&D on fossil fuel based sCO_2 cycle power systems, the US DOE has continued to invest in R&D on developing the cycles for solar, nuclear, geothermal and waste heat power (Dennis, 2014). A list of all US DOE funded sCO_2 power cycle projects can be found at DOE NETL's website (www.netl.doe.gov/research/coal/energy-systems/turbines/project-information#sco2).

In the EU (European Union) funded I-ThERM's sCO_2 project, researchers and engineers from universities and companies across the EU are working together to develop a waste heat-to-power conversion system based on sCO_2. The key objective of the project is to '*demonstrate the technical feasibility of a small 50 kW electrical sCO_2 Cycle that has superior performance in terms of efficiency and modularity to ORC* (organic Rankine cycle) *and other waste heat conversion systems for medium temperature waste heat sources*' (http://www.itherm-project.eu/).

Over 10 years ago in Japan, researchers at the Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology (TITech) began investigations of sCO_2 cycles for nuclear plants. Various sCO_2 cycle configurations were studied and designs of sCO_2 turbomachinery and recuperators were included. In June 2007, a three-year project funded by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) began at the TITech, with construction of a small centrifugal compressor test loop and cycle performance studies. More recently, R&D at the TITech was expanded to include applications to fossil fuel plants (Kato and others, 2001, 2004, 2005, 2008; Muto and others, 2006, 2008, 2010; Aritomi and others, 2011).

In South Korea, R&D on sCO_2 cycle technologies is under way at several institutes, including the Korea Atomic Energy Research Institute (KAERI), Korea Advanced Institute of Science & Technology (KAIST), Pohang University of Science and Technology (POSTECH) and Korea Institute of Energy Research (KIER).

In 2013, KAERI (in cooperation with KAIST and POSTECH) designed and constructed a 300 kWe, sCO_2 compressor test loop, the Supercritical CO_2 Integral Experiment Loop (SCIEL), to develop base technologies for sCO_2 cycle power generation systems. This features a high-pressure ratio with two compression and expansion stages. Studies in the first phase focused on compressor performance tests and establishing control logic. The loop was then upgraded to a closed sCO_2 power generation test loop in 2015 with a maximum turbine power output of 200 kWe. The objectives of the second phase study were to establish the strategy for safe operation and to develop a computer model for cycle control and analysis (Lee and others, 2013; Ahn and others, 2015; Cha and others, 2016). Other configurations, including a transcritical cycle at a temperature of 200°C are being studied. Currently, KIER is building an 80 kWe sCO_2 power generation cycle test loop consisting of a high-temperature turbine and a low-temperature turbine, one compressor and two recuperators (Cho and others, 2016).

R&D of sCO_2 power cycles for application to nuclear, solar, fossil fuel and low-grade heat sources is also being actively pursued in Australia, Canada, France, Netherlands, Spain, the UK and more recently, China and India. One of the surprising aspects of sCO_2 is the number of companies that are actively pursuing the technology, including Echogen Power Systems, 8 Rivers Capital, NET Power, GE Global Research, Électricité de France (EDF), Toshiba and Barber Nichols. In 2014, Echogen Power Systems marketed the EPS100, the first megawatt-class commercial-scale sCO_2 heat engine that is targeted for waste heat recovery or use as a bottoming cycle in gas-fired combined-cycle applications. NET Power, a collaboration between Exelon Generation, CB&I (Chicago Bridge & Iron Company), Toshiba and 8 Rivers Capitals, is developing the Allam Cycle, an oxy-combustion recuperative sCO_2 cycle for fossil fuels with full carbon capture. A 50 MWth natural gas-fuelled demonstration plant is being constructed at La Porte, Texas. 8 Rivers Capital, the inventor and developer of the technology, is also developing the system using syngas from coal gasification. The Echogen heat engine and Allam Cycle are discussed in Chapter 5.

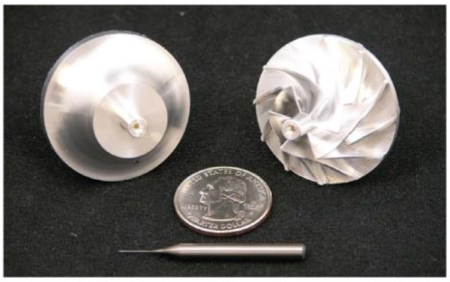
4.2 Component developments

4.2.1 Turbomachinery

Printed circuit heat exchanger

Over the past two decades, laboratory-scale sCO_2 cycle test loops have been assembled, and designs and fabrication methods developed and validated, for sCO_2 turbomachinery including bearings, seals and alternators (Moore and Fuller, 2014; Conboy, 2013; Wright and others, 2011a; 2010; Cha and others, 2016). A single stage radial turbine was used in all these small-scale test facilities. The high-energy density of the sCO_2 power cycle dictates that at 125 kWe, each turbine and compressor wheel will be only a few centimetres in diameter, as shown in Figure 6. This small size leads to high necessary shaft speeds (around 75,000 rpm), requiring specialised approaches for bearings, seals, and alternators.

a) The compressor wheel blank, the finished wheel, and one of the tools (not the smallest) used to machine the wheel in SNL's s CO_2 compression test loop (Wright and others, 2010)



b) Shrouded impeller (left), compressor assembly (centre), and turbine assembly (right) used in SCIEL (Cha and others, 2016)

Figure 6 Laboratory-scale sCO_2 turbomachinery and subcomponents

The research turbines and compressors developed to date have performed close to the design maps generated from first principles and have operated smoothly both below and above the critical temperature (Kimball, 2014; Wright and others, 2010, 2011a). Therefore, it is anticipated that there will not be a major risk in scaling up the turbomachinery design. Some researchers believe that a capacity of 7–10 MWe is the minimum size for a viable commercial design, to allow use of standard industrial components to mitigate negative consequences of leakage flow and windage loss (losses due to the friction between the rotor and fluid) mechanisms (Turchi, 2013; Fleming and others, 2012). Hofer (2016) at GE Global Research recently suggested a phased approach to move forward in a stepwise manner from a simple recuperated sCO_2 Rankine cycle at 550°C to a final configuration of a recompression Brayton cycle at 700°C or more.

While radial turbines have been tested on small-scale sCO_2 test loops, radial turbine technology is not normally used for utility-scale (≥100 MWe) power plants. Under the SunShot Initiatives Program funded by the US DOE Office of Energy Efficiency and Renewable Energy (EERE) and co-funded by GE Global Research, Thar Energy, and Bechtel Marine, GE Global Research worked with SWRI to develop a 10 MWe range sCO_2 turbo-expander for application to a sCO_2 based power cycle for concentrated solar power (CSP). The options examined are listed in Table 2. Detailed analyses of the system level impacts of each configuration allowed the researchers to identify a preferred option. The studies included detailed component designs and overall costs for each option. A second option was selected as a back-up which had a significantly lower technical risk but met the criteria less closely. The work focused on an axial turbine design with shaft speed, mass flow rate, leakage requirements, and efficiency targets as boundary conditions. The final design of the 10 MWe high-pressure, high-temperature (TIT of 715°C) sCO_2 turbine is shown in Figure 7. A model of this prototype axial turbine is shown in Figure 8. GE Global Research now hopes to scale it to 50 MWe (Kalra and others, 2014; Talbot, 2016).

Table 2 Options for turbomachinery layout and technologies (Kalra and others, 2014)

Option	Generator	Compressor	Turbine	Speed
High speed, optimal	A) Inductively coupled (IC)	A) Single stage centrifugal	A) Radial	Optimised for compressor
	B) Permanent magnet (PM)	B) Multi-stage pump	B) Axial	
High speed, expander only	A) IC	None	A) Radial	Optimised for expander
	B) PM		B) Axial	
High speed, geared	A) IC	A) Single stage centrifugal	A) Radial	Both expander and compressor run at optimal speed
	B) PM	B) Multi-stage pump	B) Axial	
	C) 3600 rpm			
3600 rpm integrated	3600 rpm	Multi-stage pump or compressor	Multi-stage Axial turbine design	3600 rpm
3600 rpm – expander only	3600 rpm	None	Multi-stage Axial turbine design	3600 rpm

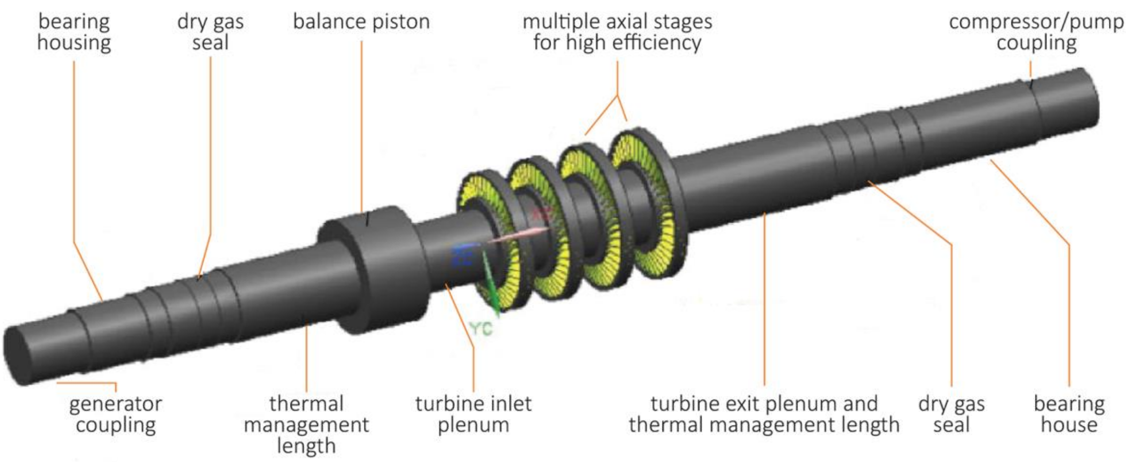


Figure 7 The 10 MWe high-pressure, high-temperature turbine rotor design developed for CSP (Kalra and others, 2014)

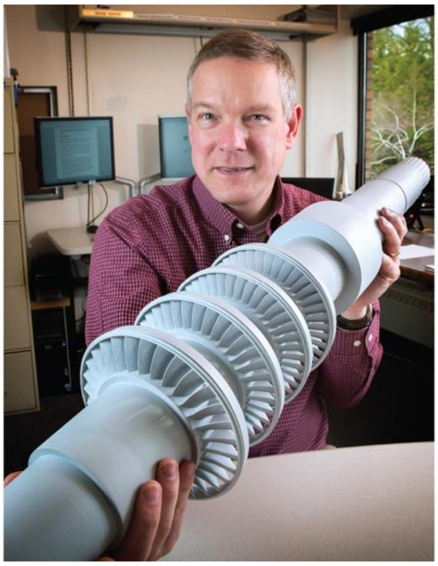


Figure 8 A model of the 10 MWe prototype turbine developed by GE Global Research shown by Doug Hofer, a GE engineer in charge of the project (Talbot, 2016)

Since 2012, Toshiba Corporation (Japan) has been developing a turbine and combustor for NET Power's 25 MWe natural gas-fuelled Allam Cycle demonstration plant that is under construction in Texas, USA (*see* Section 5.2). The turbine design essentially combines gas turbine and steam turbine technologies. Toshiba has designed a commercial-scale sCO_2 turbine in the 250–300 MWe (500 MWth) size range and scaled it down to build the 25 MWe demonstration version. Inlet pressure is 20 to 40 MPa and inlet temperature 1100–1200°C. The pressure ratio is between 6 and 12 and outlet pressure is 3 MPa. Cooling systems and thermal barrier coatings from gas turbine technology were used. Cooling CO_2 extracted from the lower temperature end of the plant is distributed to each stage through the rotor to protect both stationary and moving blades. Proven gas turbine materials were used for most of the hot gas path, since temperatures are not high when compared to those in a modern gas turbine. However, a large nickel based forging is used in the central portion of the rotor to keep the rotor design simple, minimise required cooling flow, and allow it to cope with a high torque between stages (Iwai and others, 2015).

Like a steam turbine, the sCO_2 turbine has a double shell structure (one outer casing and several inner casings to contain the high pressure systems). The space between the inner casing and outer casing will be filled with the CO_2 cooling flow, enabling the outer and larger of the inner casings to use CrMoV alloy. Ni-based material is used for the smaller inner casing that encloses the exhaust area where temperatures are higher than 700°C and moderate cooling is applied (Isles, 2014; Allam and others, 2016). Toshiba has also developed a proprietary turbine control system in cooperation with NET Power. The turbine was delivered to the construction site of the demonstration plant in November 2016 (www.webwire.com/ViewPressRel.asp?aId=206003).

Turbomachinery and key components such as seals, bearings, rotors and shafts for application in sCO_2 power cycles are being developed and tested by companies and research institutes around the world (Noall and Pasch, 2014; Monge and others, 2014; Chapman, 2016).

Compressor

MAN Diesel & Turbo SE (Germany) has developed a high-pressure CO_2 Research Rig for Advanced Compressors (CORA), comprising two compression stages integral gearing. Each stage has its own casing and, hence, multiple intercooling can be used. Inlet and outlet pressures are 12 and 25 MPa, respectively. It has a variable speed drive and a high-pressure shell-and-tube heat exchanger (HE). Tests have been carried out on the design of components such as impellers, inlet guide vanes, shaft seal and bearings. Initial results have been positive and more tests planned (Metz and others, 2015).

Wacker and Dittmer (2014) recently reviewed advanced and proven CO_2 compression technologies including reciprocating and centrifugal systems, with a focus on integrally geared designs for sCO_2 applications. The benefits and design challenges of such compressors for sCO_2 cycle applications were discussed. They believe that, for volume flows >12 kg/s and pressures up to 25 MPa, integrally geared designs have advantages over other compressor designs with higher efficiency and fewer compression stages.

A small-scale radial compressor with three different impeller designs has been installed in a closed sCO_2 test loop at TITech (Japan). Tests near the critical point of CO_2 were conducted to evaluate the design points and factors influencing compression efficiency. The test results show that the compressors with different designs all performed smoothly and effectively near the critical point as well as in a wide range of pressures from subcritical through to supercritical pressure (Aritomi and others, 2011; Ishizuka and others, 2010).

4.2.2 Heat exchangers

The heat exchangers (HEs) used in sCO_2 cycles need to meet conditions that differ from those commonly encountered on power plants. These include operation at high pressure and high temperature as well as high pressure differentials. Consequently, the design of HEs faces significant mechanical, thermo-mechanical, and thermal-hydraulic challenges. Apart from giving a sufficiently high rate of heat transfer at as small as possible a pressure drop, other factors include the possibility of erosion and corrosion in the unusual environment. The heat exchanger type, design, material selection and cost are key elements in HE development, and compact heat exchangers (CHE) are recognised as best suited for the purpose. Nevertheless, the cost of the heat exchangers (HEs) can amount to a significant fraction (30% or more) of the total system cost.

Printed circuit heat exchanger

The printed circuit heat exchanger (PCHE), developed for use at very high pressure in the oil, gas and chemical industry, has been the most widely used recuperative type of HE for sCO_2 power cycle development testing. This is because there is an established method for its manufacture, it is effective, robust, compact and capable of withstanding high pressures. The PCHE concept enables operation at simultaneous high temperature and pressure with relatively thin walls between primary and secondary cooling. PCHE can withstand pressures of over 60 MPa, and operate at temperatures ranging from cryogenic to 900°C with close temperature approach (www.heatric.com). PCHEs are plate-type CHE in which flow channels (typically with a small hydraulic diameter) are chemically etched into thin, flat metal plates. The etched plates are stacked together with a prescribed configuration and are diffusion bonded (a solid-state joining process) to create a high-integrity solid block. Headers, nozzles and flanges are usually welded to the PCHE block to constitute the whole of the heat exchanger. PCHEs can adopt various configurations for a given application to take advantage of the etching and diffusion bonding process to create geometries for optimal performance.

There are many types of channel geometry, including straight, wavy (zig-zag), S-shaped fin, and airfoil-finned channel (*see* Figure 9). This provides flexibility in the design of PCHE configurations so that pressure drop and heat transfer can be optimised to give high efficiency. Studies have been carried out to identify optimum channel design for efficient PCHE and the designs continue to be developed (Ngo and others, 2007; Tsuzuki and others, 2007; Kim and others, 2008; Zhang and others, 2016).

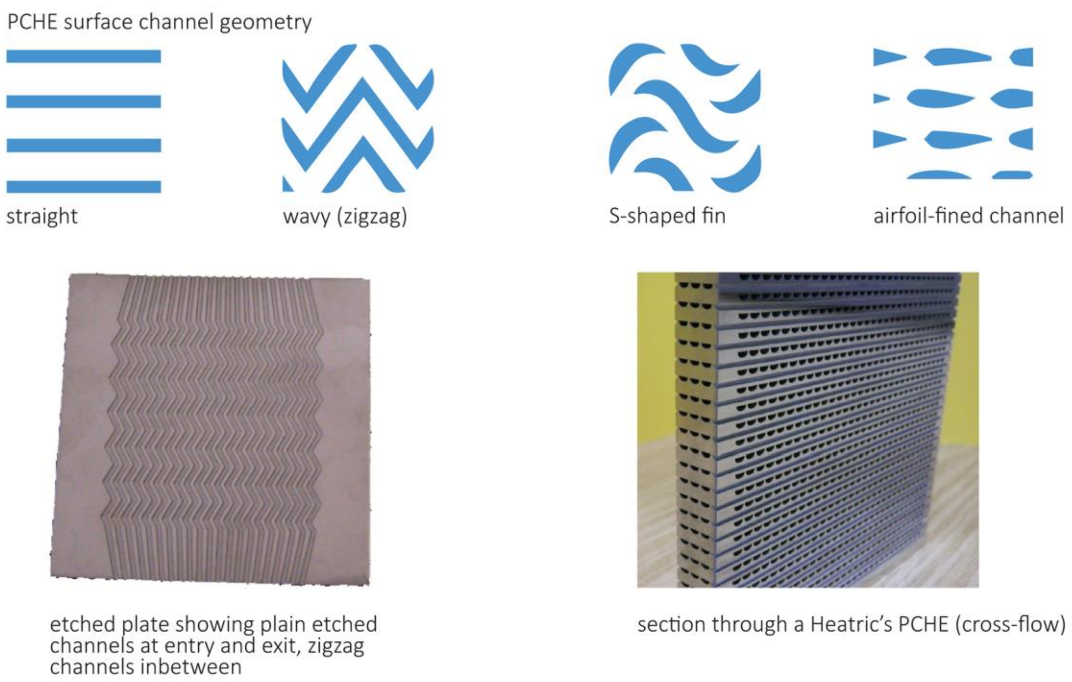


Figure 9 Examples of the PCHE design

Heatric (UK) has been manufacturing PCHE for over 30 years and more than 1000 units have been sold, mainly in the oil and gas industry. The design considerations, material selection, configuration options and manufacturing methods of PCHEs for potential application in the nuclear power industry are discussed in detail by engineers at Heatric (Southall and others, 2009; Southall, 2009; Li and others, 2009; Southall and Dewson, 2010; Le Pierres and others, 2011). Heatric's PCHE were used in SNL's sCO_2 test loop (*see* Chapter 2) for the cooler, low temperature recuperator and for a high temperature recuperator and in Echogen's EPS100 (*see* Chapter 5). In 2015, Heatric signed a contract to supply four PCHEs to NET Power's Allam Cycle demonstration power plant in Texas, USA (Heatric, 2015; Le Pierres, 2016). Other manufacturers such as Vacuum Process Engineering (VPE, USA) and Kobe Steel (Japan) are also developing PCHE.

While robust PCHE can be produced for sCO_2 recuperator applications, this type of HE is expensive due to the cost of creating the chemically etched channels and the cost of the diffusion bonding process. To effectively diffusion bond a stack of plates, the surface of all plates must be extremely flat and clean. The stack is heated in a furnace under a pressure of around 27 MPa and temperatures that are near the melting point of the base material for several hours. For sCO_2 power cycle applications, the cost of PCHE recuperators could account for 20–30% of the total plant cost, which means that reducing this cost would improve the economic competitiveness of the cycles. Also, it has been reported that a typical PCHE could fail within 300 to 800 complete thermal cycles. Under severe thermal transient conditions, it could fail nearer to 200 cycles (Carlson and others, 2014a). Work is ongoing to understand how to predict thermal fatigue in these units, and how to improve designs and fabrication methods of PCHE to optimise efficiency and reduce costs.

The diffusion bonding process of PCHE requires solid stack structures that support the high compression loads needed for good diffusion bonding so the resultant PCHE can withstand pressures up to 60 MPa as required for oil, gas and chemical applications. Altex Technologies Corporation (USA) recently developed High Effectiveness Low Cost (HELC) recuperators as test units, using materials, design, fabrication and bonding processes suitable for sCO_2 power cycle applications with a lower peak pressure of around 24 MPa and temperatures up to 700°C. For the given maximum temperature and pressure in closed-loop sCO_2 cycle applications, an HELC with a solidity of 52.6% (compared to 63.6% for PCHE) can meet the USA's American Society of Mechanical Engineers (ASME) pressure vessel code requirements. A load-assisted vacuum brazing fabrication process that uses the braze filler material is adopted to address surface flatness imperfections and, in particular, to tolerate mismatches between plates, frames and inserts. Several channel geometries such as rectangular channels that have higher surface area to volume ratios than the channel geometry used by conventional PCHE were selected and tested to identify potential candidates for the HELC. The developers claim that this design can reduce recuperator volume by over 45% and weight by over 54% compared to the conventional PCHE approaches for the same heat duty. With the reduction in recuperator weight, material costs will be reduced by a similar proportion. Also, less expensive steel alloys can be used to construct HELC. Besides the reduced weight, material cost and higher surface area to volume ratios, an HELC has 78% fewer bond joints and parts per volume than the current PCHE designs leading to further cost savings (Kelly and others, 2016). Two 30 kWth HELC test articles were built and tested. More tests were planned with the aim of designing and fabricating a 500 kWth test unit to demonstrate the HELC manufacturing at small scale.

Since May 2014, SNL has had a Cooperative R&D Agreement (CRADA) with VPE. This work is funded by the US DOE Office of Nuclear Energy. PCHE is a strong candidate technology for use in a 10 MWe sCO_2 cycle demonstration system under the Supercritical Transformational Electric Power (STEP) initiative. Initial work involved tests to understand bond failure and evaluate a Diffusion Bonding Procedure Specification (DBPS) A Selection, Evaluation, And Rating of Compact Heat exchangers (SEARCH) design tool has been developed to automate and simplify the design of PCHEs. A 100 kWth prototype PCHE was constructed in 2015 for thermal-hydraulic testing in a water-water test loop, designed for temperature approaches of

>15°C and an approximately 60 kPa of pressure drop. Straight channels were used. Tests have been carried out for the validation of design algorithms. Additional activities are also planned to reduce other PCHE costs including plate and header fabrication (Carlson and others, 2016).

Plate-fin heat exchanger

The Plate-fin heat exchanger (PFHE) consists of fins which are bound by side bars and separated by flat parting sheets. These layers are built-up to accommodate various flow patterns, such as counter-current flow or cross-flow, depending on requirements. The formed plates are stacked and then either brazed or diffusion-bonded to make a core heat exchange unit. Figure 10 shows the key components of a brazed PFHE.

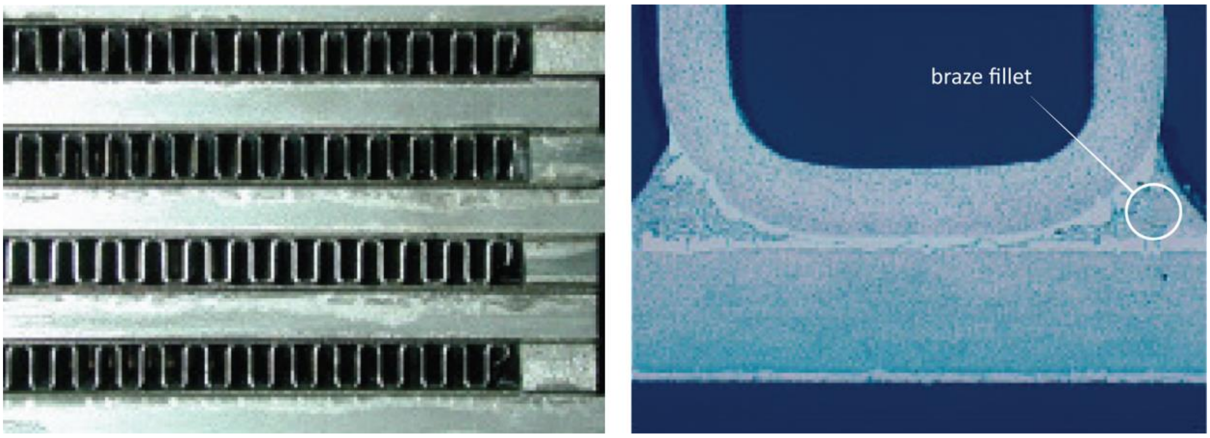


Figure 10 Components of brazed plate fin-heat exchanger (Modified from Kesseli and others, 2007)

PFHEs have been widely used as gas turbine recuperators and have proved their integrity in the extreme environment of a gas turbine with high temperature and high temperature differentials (higher than those of sCO_2 cycles), rapid thermal transients but moderately high pressures and moderate differential pressures (<1.5 MPa). In the last decade, development of recuperators for advanced nuclear reactors using sCO_2 and helium Brayton cycle has resulted in a design for higher pressures and pressure differentials (Kesseli and others, 2007; Carlson and others, 2014b).

A different plate-fin design approach has been taken by Ingersoll-Rand which can handle moderately high temperatures (530°C) and pressures, and a pressure differential of 1.5MPa, and it is especially suitable for demanding temperature transients. These designs can use both brazed and diffusion bonding methods, and were being considered for recuperator service in the sCO_2 power cycle and for the sCO_2 heaters in next generation nuclear plant, as described by Kesseli and others (2007). The recommended design for application in sCO_2 cycles is shown in Figure 11. The key to the design is the unit cell which consists of two partition plates supporting a single corrugated, high pressure cell fin row. Secondary side fins are brazed or bonded to the outside of the partition plates. The partition plates and pressure cell fin row are brazed or bonded to form a single layer, high-pressure cell with attached secondary side fins. Pressure can be supported within the pressure cell layer without the aid of a strong back or cage. This produces a stack of cells with much higher internal flexibility than the solid core.

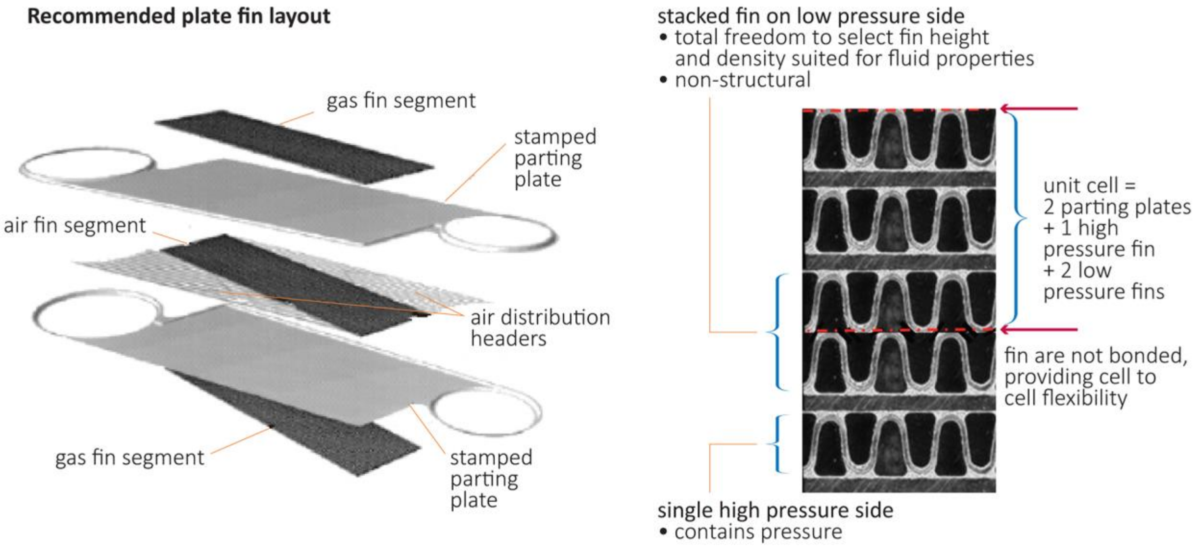


Figure 11 Recommended PFHE design for recuperator services in sCO_2 cycles (Kesseli and others, 2007)

Brayton Energy, LLC (US) has been working to develop HEs for applications in solar thermal energy using a sCO_2 power cycle. Supported by the US DOE under the SunShot Initiative, Brayton has developed a sCO_2 solar receiver design that incorporates several unique characteristics such as a matrix of extended heat transfer surfaces in the form of densely-packed folded fins brazed within an external shell, as shown in Figure 12. This provides a high degree of geometric flexibility, allowing specifications to be tailored to operating conditions. The sCO_2 solar receiver is designed to operate under conditions of 25 MPa and 750°C (outlet), and an efficiency of 54%. A cell-based cap-and-sleeve manifold design is adopted resulting in a small, lower-cost and lightweight HE (Sullivan and others, 2016).

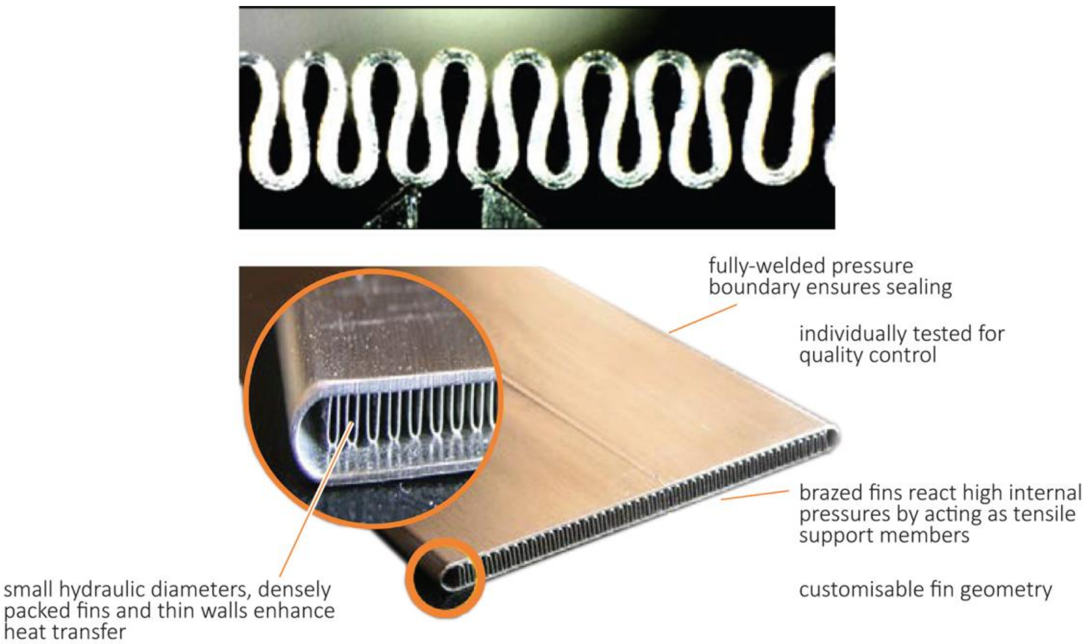


Figure 12 The geometry of densely-packed folded fin (top) and the basic sCO_2 solar absorber panel design (bottom) (Sullivan and others, 2016)

Various types of fin geometry have been developed to increase the heat transfer surface area and coefficient. As an example, PFHE with wire-mesh as the heat transfer surface can achieve a surface area density of 7000-8000 m^2/m^3 compared to 4000-5000 m^2/m^3 for a similar PFHE with wavy-fins. As a result, the HE with wire-mesh is the more compact and expected to achieve an even higher power density and the required fatigue endurance at a competitive cost (*see* Figure 13) (Fourspring and others, 2014; Musgrove and others, 2014; www.braytonenergy.net/heat-exchangers/).

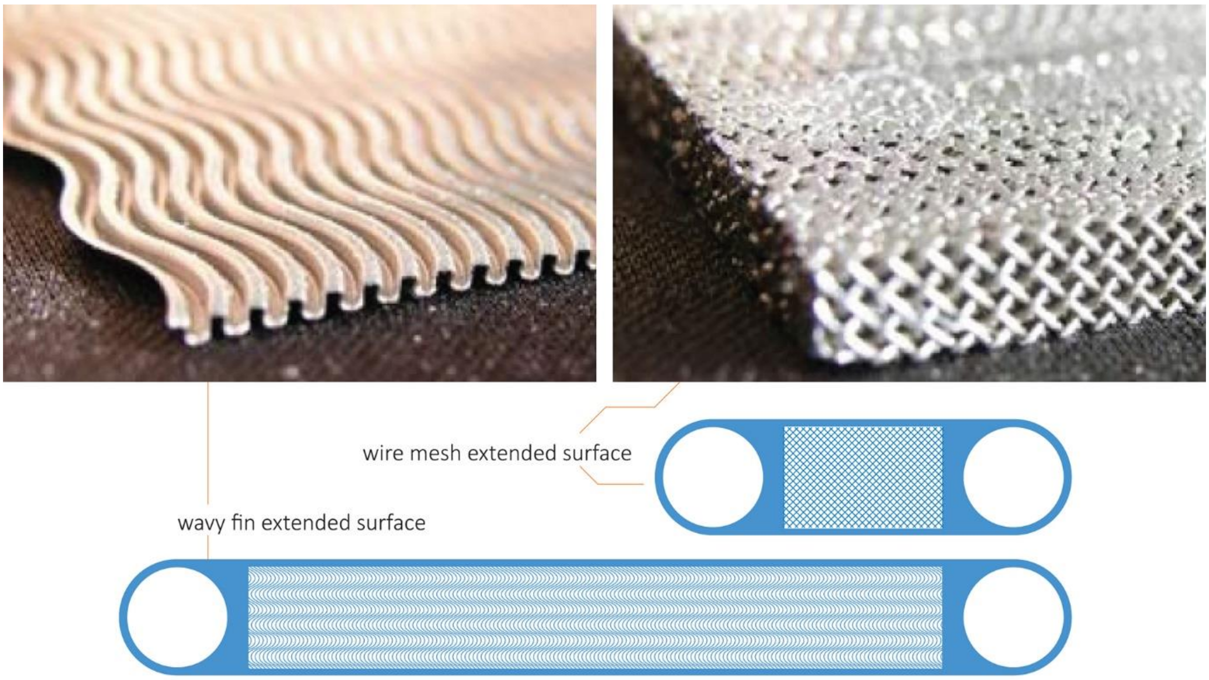


Figure 13 Comparison of a wire-mesh heat exchanger unit-cell and a wavy-fin unit-cell with same capacity (Musgrove and others, 2014; Fourspring and others, 2014)

Cast metal heat exchangers

SNL is pursuing a novel cast metal heat exchanger (CMHE) as a medium-term solution to recuperation in sCO_2 cycles. It could offer performance similar to or better than PCHEs but at less than a fifth of the cost while allowing greater flexibility in materials and channel geometries. The CMHE concept is based on the interconnectivity of the flow channels proposed for advanced PCHE surfaces such as the S-shaped and airfoil-fins shown in Figure 9. Constructing the highly-interconnected channel spaces of these surfaces produces a casting core more like a perforated plate. The casting core would be slotted into polymer-bound sand or investment casting moulds to produce a heat exchanger in a single casting operation. While advanced PCHE surfaces interconnected in two dimensions can be emulated, interconnection can also extend into three dimensions as shown in Figure 14, giving enhanced heat transfer with minimal increase in pressure drop. Such a casting core could be created using powder-bed 3D printing techniques.

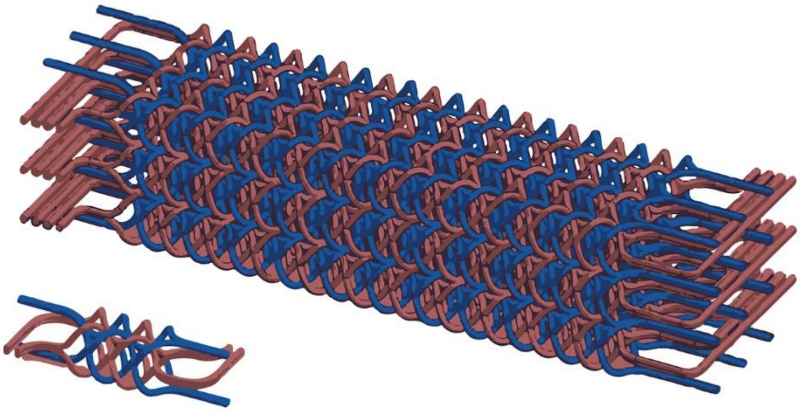


Figure 14 A counter-rotating double-helical geometry proposed for use in a CMHE between two similar fluids: red channels for hot flow and blue for cold flow (Carlson and others, 2014a)

Casting has long been used to reduce the cost of a component by reducing the number and complexity of fabrication steps involved. Figure 15 compares the plate processing steps involved in producing PFHE plates using brazing or direct-casting. In a CMHE, several HE elements are fabricated into a larger unit, an option particularly attractive for high-performance nickel alloys, where the machining required for plate, shell, and wire product forms is difficult.

Figure 15 A comparison of the plate processing steps involved in producing a PFHE using brazing or directly-cast plates (Carlson and others, 2014a)

The developers believe that CMHEs hold great potential for reducing the cost of sCO_2 HEs. However, there is limited industrial experience with these fabrication techniques. The most critical challenge will be finding methods and techniques for removing casting core material from the finished block. Castability of various HE-channel geometries will be the next major challenge. Centrifugal or pressure-casting techniques may be needed for tight clearances with highly viscous melts (Carlson and others, 2014a).

Ceramic, microchannel heat exchangers

The main advantages of ceramic materials over traditional metallic materials in CHE construction are their extremely high temperature stability, low material cost and excellent resistance to corrosion and chemical erosion. Ceramatec Inc (USA) has recently developed innovative microchannel designs and manufacturing methods to produce scalable, cost-effective ceramic recuperators with high reliability, high heat transfer efficiency, and low pressure-drop suitable for deployment in large-scale power cycle applications. Fabrication consists of producing microchannel plates and then bonding them into stacks. Powder or raw materials prepared with the desired chemical and physical properties are blended into a solvent with organic binders, plasticisers and other additives to produce a slip suitable for tape casting. Various combinations of blade geometry, viscosity, and drying arrangements are used to cast rolls of tape ranging from one to several hundreds of micrometres thickness. The tape can be featured by laser cutting or punching to introduce the regions that will become microchannels. A wide variety of microchannel designs can be obtained in this way, as shown in Figure 16. The plates can be assembled into stacks using sealants including ceramic inks, glasses, brazes, and diffusion bonding. Stacks are then connected by manifolds. The design is such that the temperature of the ceramic to metal joints is relatively low and, hence, standard ceramic-to-metal joining methods such as brazing can be used.

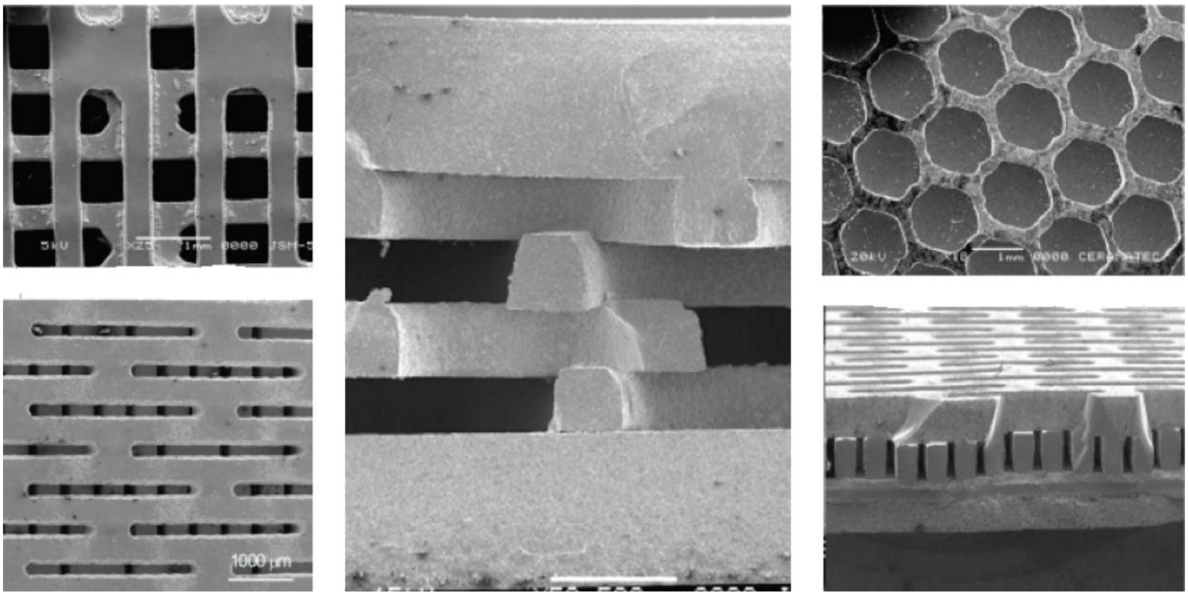


Figure 16 Examples of features available in microchannel designs (Lewinsohn and others, nd)

By using well-established commercial manufacturing techniques, the production costs of ceramic HEs can be competitive. Ceramatec claim that ceramic microchannel HEs are highly effective, compact, easy to manufacture and have excellent creep resistance and low costs. The size of a heat exchanger stack for a 5 MW power system would be about 0.15 m^3. Also, compared to superalloys, ceramic HEs can withstand temperatures up to 150°C higher and greater pressures due to their superior creep and oxidation resistance (Lewinsohn and others, 2016). However, ceramic HEs are still under development. Barriers to overcome include their intrinsic brittleness in tension, difficulties in shaping and sealing and high manufacturing costs. They cannot withstand large thermal gradients and, except silicon carbide and silicon nitride, are susceptible to thermal shock failure. Major research efforts are focused on less brittle ceramic materials such as composites.

Several other types of HE, such as shell and tube, plate and shell, hybrid exchanger and porous media (metallic foam) exchanger have also been considered and assessed for application in sCO_2 power systems (Carlson and others, 2014b; Musgrove and others, 2014).

4.2.3 Materials

The peak operating conditions of proposed indirectly- and directly-heated sCO_2 power cycles present challenging requirements for construction materials' strength and environmental resistance. Key components of concern are the turbine, HEs and combustor (for semi-closed sCO_2 cycle). Extensive tests have been conducted worldwide to identify materials compatible with high temperature, high pressure sCO_2 operation and the performance requirements of individual components. Wright and others (2013) discussed the requirements unique to sCO_2 cycles and the issues to consider during materials selection. They reckoned that materials selected for advanced ultrasupercritical steam systems would be a good starting point and that alloys used in conventional gas turbines could potentially be candidate materials for closed-cycle sCO_2 turbines. Superalloys such as A286 or IN706 might be needed in closed-cycle sCO_2 turbines to avoid the need for blade cooling, whereas lower-cost alloys such as NI55 would be expected to have adequate creep strength for airfoils when blade cooling is used. Due to the higher temperature and pressure, nickel-based alloys such as IN738 might be required for the turbine in the Allam Cycle. Some HEs in the proposed sCO_2 cycles will need to handle sCO_2 at temperatures up to around 640°C (closed-cycle) and 700–750°C (semi-closed cycle) and, in addition, to experience a significant pressure differential across the walls of casings or tubes in contact with the ambient environment; the same considerations apply to casings of turbines and compressors. Wright and others (2013) suggested that ferritic steel could be used for recuperative HEs in closed-cycle systems with a maximum pressure of 20 MPa.

In earlier studies, corrosion and carburisation of metals in high temperature sCO_2 (>500°C) were observed. The corrosion and erosion mechanisms in sCO_2 cycles were described by Fleming and Kruizenga (2014). The mechanisms and kinetics of oxidation and carburisation of metal alloys in high temperature sCO_2 were discussed by Rouillard and Furukawa (2016). A large number of studies are available on creep, corrosion, oxidation and carburisation behaviour of alloys. These tests were typically conducted in pure CO_2 and generally in a temperature range of 400–750°C and pressures up to 20–25 MPa with exposure time ranging from a few hundred to 8000 hours. Many of the tests were carried out on Cr-containing iron-based alloys but tests on Ni-based alloys and Fe- or Ni-based alumina forming alloys were also performed (Rouillard and Furukawa, 2016; Fleming and others, 2014a,b; Furukawa and others, 2010; Oh and others, 2004, 2006; Lee and others, 2014; Mahaffey and others, 2014; Saari and others, 2014; Holcomb and others 2016; Keiser and others, 2016; Pint and Keiser, 2014; Pint and others, 2016a). Studies on welding of superalloys and coating techniques for material applications in sCO_2 power systems are also underway (de Barbadillo and others 2014; Pint, 2015; Kapoor and others, 2016). Results from these studies indicate that in general:

- the degradation due to corrosion, oxidation and carburisation of the tested materials in sCO_2 is insignificant in temperatures lower than 500°C;
- the corrosion/oxidation rate of the tested materials increases with increasing temperature whereas the sCO_2 pressure has minimal effects; and
- high concentrations of chromium and nickel significantly increase the corrosion resistance of steel alloys; and higher-alloyed materials perform better than lower-alloyed materials in high temperature sCO_2. The corrosion/oxidation rate generally decreases with increasing Cr concentration of the alloy,

and austenitic steels are more resistant to sCO2 induced corrosion than ferritic-martensitic steels within the test temperature range.

Some test results also suggest that formation of a continuous surface film of chromia (Cr-containing alloys) or alumina (alumina-forming alloys) is possible in sCO_2 at temperatures of <700°C, which exhibits protective oxidation behaviour. At higher temperatures, only Ni-based alloys form a protective layer. However, there is some evidence that the oxide scale formed on the surface is prone to spallation under certain conditions that could cause erosion of system components. Even where protective scales are formed, it appears that carburisation of the underlying alloy, particularly to the lower-alloyed steels, could result from ingress of carbon-containing species through the oxide scale formed on the alloy surface and subsequent reaction at the metal-oxide interface.

In oxy-combustion sCO_2 cycles, it is expected that some low levels of impurities such as O_2, H_2O, hydrocarbons and NOx/SOx (fossil-fuelled, semi-closed cycles) will be present. Studies are ongoing to investigate the impact of the impurities on the stability, creep and corrosion properties of the structural materials. Laboratory tests show that the tested materials exhibit higher corrosion resistance when low levels of O_2 and H_2O are present compared with pure CO_2 under the same conditions (Kung and others, 2016; Pint and others, 2016b; Mahaffey and others, 2014). This may be attributed to the higher oxygen partial pressure that promotes the formation of protective oxide scales. More work is needed to understand better the material interactions with sCO_2 under operating conditions and to generate data needed for the design and construction of key components.

4.2.4 Oxyfuel combustor

Toshiba has been developing an oxyfuel combustor for NET Power's Allam Cycle. Compared with typical heavy-duty gas turbines, the combustion process of the cycle is characterised by its moderate combustion temperature, high pressure and different combustion environment. It requires oxyfuel combustion at approximately 30 MPa and 1150°C TIT. A non-premixed diffusion flame design is applied with the inlet temperature above auto-ignition to mitigate the risk of auto-ignition. A small-scale test rig using a simple single swirler device was tested first. NOx formation is not a concern, hence flame temperatures can be selected for best performance, operability and durability. The test facility is a 1:10 scaled down Allam Cycle combustor (Figure 17). Oxygen and CO_2 are mixed (between 15% and 40% O_2 by mass) upstream of the combustor. Flame temperatures are about 2097–2207°C, consistent with conventional diffusion-flame gas turbine combustors. The oxidant enters the combustor after passing through a set of swirl vanes, which results in a stream with both axial and circumferential velocity components to improve combustion efficiency. The oxidiser stream creates a stable vortex analogous to conventional gas turbine systems. It uses proven cooling technology, such as convection cooling, due to the moderate combustion temperature and the high cooling capability CO_2.

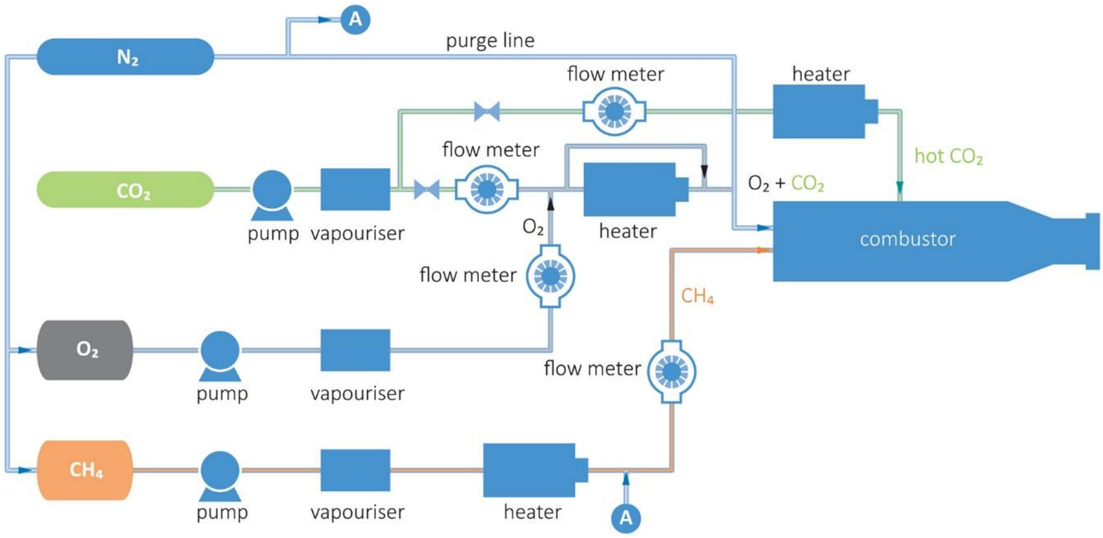


Figure 17 Toshiba's 30 MPa oxy-combustion test system (Iwai and others, 2015)

The combustor has been designed for a gas pressure of 30 MPa, more than 10 times the gas pressure used in conventional gas turbines. Computational codes and computational fluid dynamics (CFD) were used to calculate the heat transfer, fluid and mixture properties. Initial tests using the 5 MWth facility showed good operability over a wide range of O_2/CO_2 ratios with metal temperatures close to predicted values, proving the feasibility of the design. The tests have been used to acquire a wide range of operational data for the design and construction of the oxy-combustor for NET power's natural gas-fuelled, 25 MWe sCO_2 demonstration plant (Iwai and others, 2015; Allam and others, 2013; Isles, 2014).

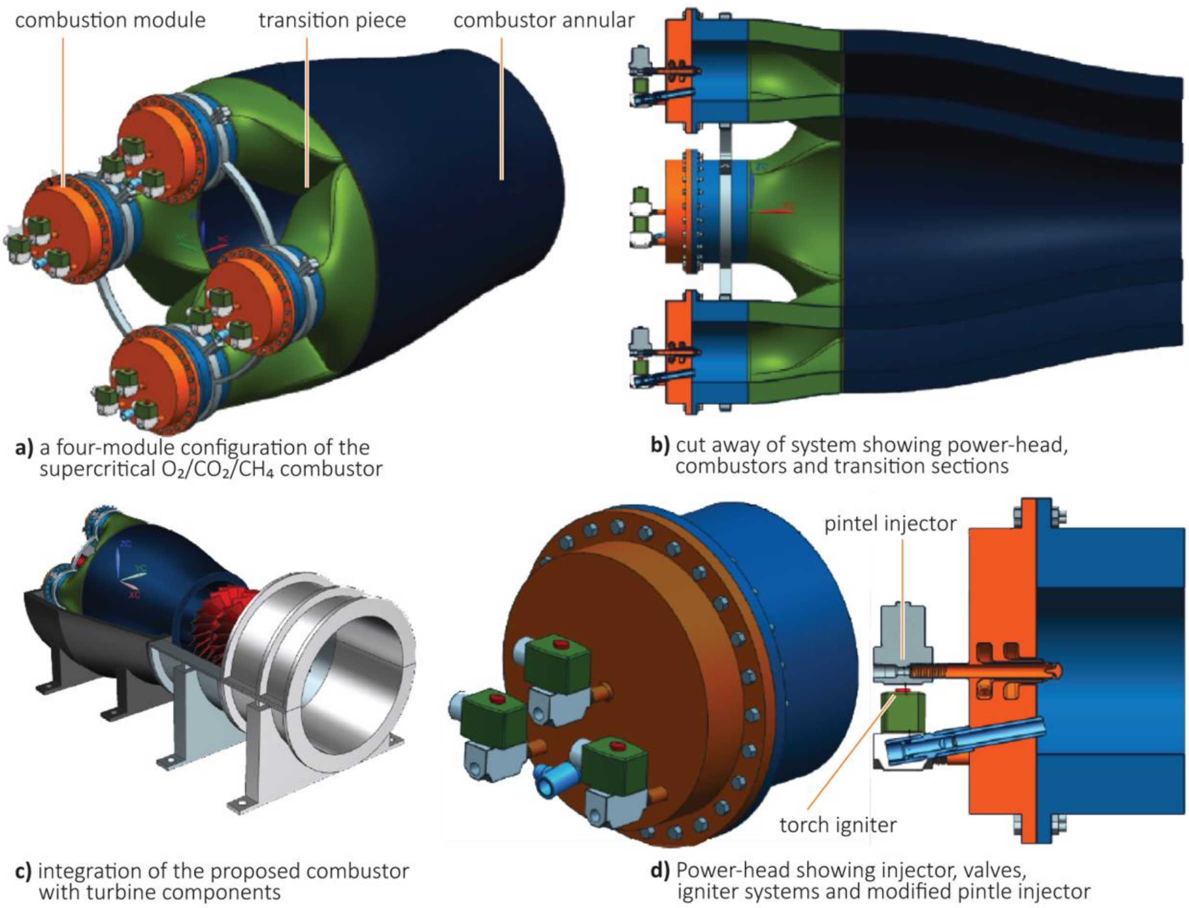


Figure 18 Oxyfuel combustor design developed by the University of Texas (modified from Chowdhury and others, 2015)

Researchers at the University of Texas (USA) have developed a conceptual design for a natural gas-fuelled, oxyfuel combustor for a 300 MWe turbine. The design is based on a liquid oxygen (LOX)/methane rocket engine, as shown in Figure 18, and has two major advantages: 1) the use of existing technologies and 2) a modular design that can be modified to be compatible with current or similar power turbine layouts. Figure 18a shows a four-module configuration of the combustor. Three- and five-module configurations may be considered as well for scaling analysis. Each module comprises a power-head, combustor-body, and transition piece to mesh with the combustor annulus (Figure 18b and 18c). The power-head consists of injector elements, valves, and a torch igniter (Figure 18d). In the proposed configuration, the working fluids are delivered from four different power-heads, distributed equally at the combustion chamber inlet and connected to the combustion chamber through a transition module. A bell shape geometry is chosen for the combustion chamber to achieve uniform mixing of the working fluids from four different powerheads to maximise turbine output.

The pintle injector design has been adopted due to its scalability, enhanced mixing, high performance and combustion stability as well as ease of manufacturing. It has a long history of use in rocket engines. Mixing is based on the intersection of outer-axial and inner-radial propellant flow at the injector face, as illustrated in Figure 19b. A computational model has been developed to analyse the mixing of the working fluid inside the combustion chamber. The analysis showed that the injector can achieve high turbulence levels, leading to uniform mixing, and the bell shape geometry of the combustion chamber acts to dissipate instabilities and creates a uniform fluid stream (Chowdhury and others, 2016, 2015). Tests are needed to validate the design.

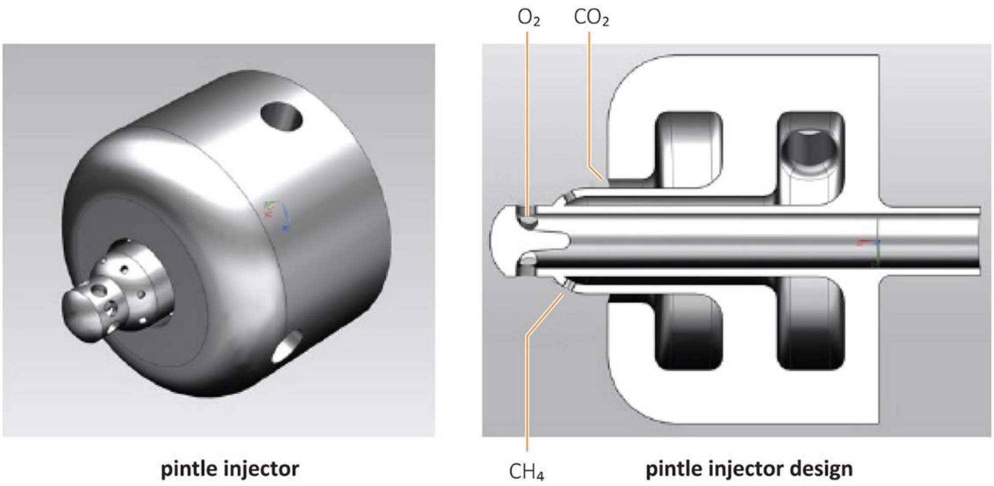


Figure 19 Design concept for a pintle injector and a pintle injector design (Chowdhury and others, 2016)

SWRI, in partnership with Thar Energy, LLC, is working to develop a high inlet temperature supercritical oxy-combustor suitable for a natural gas- or syngas-fuelled sCO_2 power cycle with a target plant efficiency of 52% (LHV). System design and thermodynamic analyses have been conducted to determine the optimum cycle configuration and combustor design parameters such as inlet temperature, pressure and mass flow. A kinetic model has been developed and initial evaluation of the combustion kinetics at combustor inlet conditions carried out. An auto-ignition based combustor design has been developed and bench-scale tests are being performed. Further design studies using parametric CFD simulation, cooling flow simulation and structural simulation will be carried out and a demonstration-scale oxy-combustor will be designed (McClung and others, 2015). Theoretical and numerical investigations of auto-ignition and combustion stability of high pressure sCO_2 oxy-combustion are under way at Georgia Institute of Technology (USA) (Sun and others, 2015).

A design for a swirl type supercritical oxy-combustor for solid fuel has also been developed at SWRI using computer modelling to provide initial assessments of the coal combustion reactions in the flow path. The design effort included initial combustor mechanical layout, initial pressure vessel design, and the conceptual layout of a pilot-scale test loop.

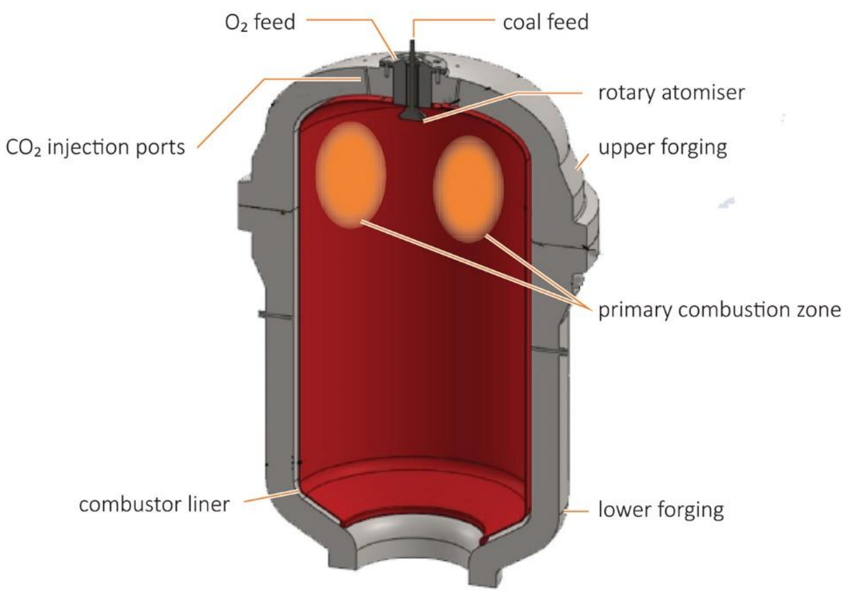


Figure 20 The swirl type supercritical oxy-combustor for soild fuel (McClung and others, 2014)

As illustrated in Figure 20, the combustor injects a coal-water slurry or coal-CO_2 slurry into the top of the combustion chamber. This slurry is distributed evenly in the combustion zone using a rotary atomiser. Diluent CO_2 is injected into an annulus formed by the combustor casing and a porous thermal barrier, providing cooling to the liner as it flows. The location of the combustion zone is controlled by the location of the O_2 injectors and mixing of the fuel and oxidiser in the combustion chamber. The hot flue gas, inorganics, and any solid combustion by-products flow down and exit the combustion chamber into hydro-cyclones for particulate removal (McClung and others, 2014).

4.2.5 Other developments

Researchers at the US DOE Argonne National Laboratory (ANL) have developed the Plant Dynamics Code (PDC) for system level analysis of sCO_2 cycles. This has been used extensively for cycle design as well as the development and refinement of control strategies. Current activities are focused on testing and validation of PDC using data available from small-scale sCO_2 cycle testing and demonstrations (Moisseytsev, 2016; Moisseytsev and Sienicki, 2016, 2008). A complete dynamic system model for the SNL's sCO_2 compression test loop has been developed in RPCSIM (Reactor Power and Control SIMulator) code to analyse system performance. Computer simulation systems are also used for detailed analyses of operational performance characteristics such as losses, leakage, windage and compressor performance (Anderson and others, 2014; Wright and others, 2010, 2011b).

A large number of computational models have been developed around the world for performance and economic analyses, assessments of the chemical kinetics of sCO_2 combustion and thermal dynamics of heat transfer and for comparisons of different cycle configurations (Hume, 2016; White, 2014; Dyreby and others, 2013; Nassar and others, 2014; Boys and others, 2016; Vasu and others, 2016; Carlson and others, 2016; Hruska and others, 2016).

Recently, SNL signed a three-year cooperative research and development agreement (CRADA) with Peregrine Turbine Technologies, Xdot Engineering and Analysis and Flowserve Corporation (all in the USA) to develop key components. Peregrine is working with SNL on a heat exchanger that can cope with the high thermal stresses from large temperature swings. Xdot is developing a foil bearing that supports a turbine shaft spinning at high speed in sCO_2. Flowserve is designing a high-intensity seal for power turbines at 700°C and 30 MPa. This has a dynamic gasket that is able to slide and seal. SNL lets its partners run tests on its closed sCO_2 cycle test loop and test rigs for bearings and seals. All three companies have developed prototypes, with Sandia's technical input and testing made possible by the CRADAs (www.azocleantech.com/news.aspx?newsID=23966).

Pipe size selection and piping design are important to reduce thermal expansion stresses and to accommodate the flange loading effects on the turbomachinery, heaters, recuperators and gas coolers. The cost of piping and related equipment is estimated to account for approximately 7–8% of the total construction cost. Therefore, optimal piping design can improve the overall performance and reduce the capital cost of the plant. Kim and others (2015) discussed criteria for pipe selection for sCO_2 cycles. The piping configuration for SNL's recuperated, closed Brayton test loop is described by Wright and others (2011a).

In summary, extensive R&D activities are ongoing to develop sCO_2 cycles for power generation. Significant progress has been made in many areas such as development of the design and construction of the key components, identifying suitable materials and establishing computer models for fundamental studies and system analyses.

5 Developments in sCO_2 power systems

Two main sCO_2 systems are suitable for applying to coal firing: directly- and indirectly-heated cycles. Various configurations have been proposed and studied. Developments are described in this chapter.

5.1 sCO_2 power cycle variants

5.1.1 Indirectly-heated closed cycles for coal-firing

A number of variations to the simple indirectly-heated sCO_2 Brayton cycle have emerged over the years. Figure 21 shows some examples of these.

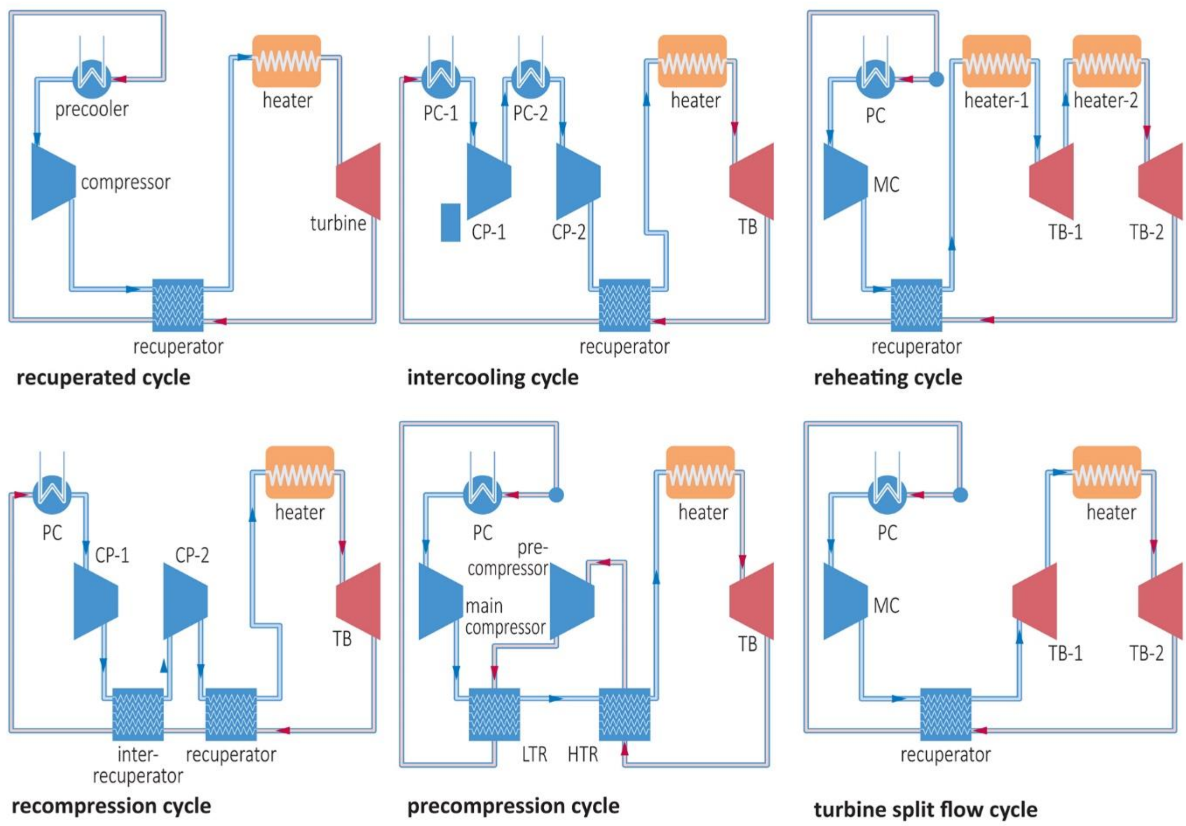


Figure 21 Examples of the proposed sCO_2 Brayton cycles (Ahn and others, 2015)

Mecheri and Le Moullec (2016) analysed several sCO_2 cycle configurations for coal power and concluded that an indirectly heated recompression cycle is essential for high-efficiency coal-fired sCO_2 power plant. Adding a single reheat results in 1.5% points efficiency gain over non-reheat cycles. Other process improvements such as a double reheat cycle, double recompression cycle and an advanced flue gas economiser configuration can lead to an efficiency gain of between 0.3 and 0.5% points.

In the project 'High-efficiency thermal integration of closed supercritical CO_2 Brayton power cycles with oxyfired heaters' funded by US DOE/NETL, Miller and others (2017) analysed a number of cycles with different layouts and subsystems such as cooling methods and air preheating. sCO_2 power cycles integrated with an oxy-combustion coal power plant (550 MWe net power output) were chosen and a cascade cycle and a recompression cycle were used as baselines. The cascade cycle is a recuperated closed cycle with high-temperature and low-temperature recuperation and heat extraction in three stages from the primary heat source, which is used in the heat engine developed by Echogen (*see* Section 5.3). The baseline recompression cycle (RC) analysed had a high temperature compressor between the CO_2 cooler and low temperature recuperator, but used a single primary heater. The sCO_2 stream leaving the primary heater is split into two (cascade cycle) or three (RC). Two of the RC variations studied included the RC with low-grade heat recovery (RC-LG) and the RC-LG with multiple compression stages and turbine reheat (*see* Figure 22). In the RC-LG cycle, the sCO_2 stream exiting the low-temperature compressor passes through a low-temperature recuperator (RHX2) and is then mixed with the sCO_2 stream from the high-temperature compressor. The mixed stream is split into two, one flows through a low-grade heat recovery system (PHX2) and the other is heated in a high-temperature recuperator (RHX1). The two streams then merge and enter the primary heater (PHX1). A MATLAB based optimisation software developed by Echogen was used for evaluation of the cycles. TITs of 593°C and 730°C were selected. The results showed that the recompression cycle and variants performed better than the cascade cycle. Potential efficiency gains of 3.3 and 4% points could be achieved at TITs of 593°C and 730°C, respectively. The air preheater inlet temperature had a significant impact on performance: with increasing air preheater inlet temperature, up to 5% points efficiency gain could be achieved. Direct CO_2 to air cooling using an air-cooled condenser was identified as the preferred option: direct water cooling was not a viable option for PCHEs.

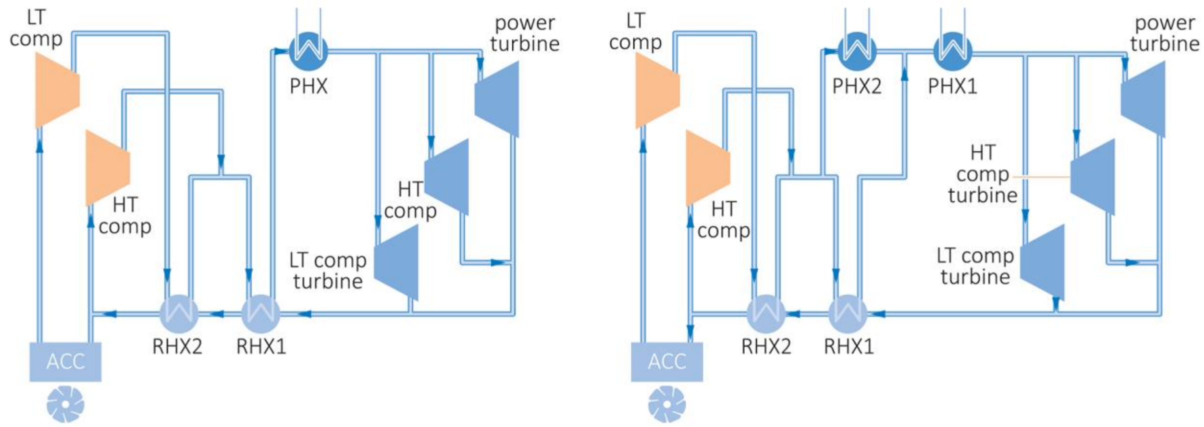


Figure 22 The layout of baseline RC cycle (left) and RC-LG cycle (Miller and others, 2017)

As part of NETL's systems analysis efforts, Shelton and others (2016) investigated the performance of a power plant based on the sCO_2 recompression cycle indirectly heated by a coal oxyfired ACFB (atmospheric circulating fluidised bed) boiler and compared it to a reference oxyfired ACFB supercritical steam cycle power plant. The sCO_2 cycle was thermally integrated with the plant via the ACFB and a flue gas heat exchanger. Four configurations for the sCO_2 recompression cycle were analysed: 1) a recuperated, recompression sCO_2 cycle (baseline); 2) a recuperated, recompression cycle with reheat, in which the sCO_2 exiting the high-pressure turbine (HPT) is returned to the ACFB furnace to be reheated before it is expanded in the low-pressure turbine (LPT); 3) a recuperated, recompression cycle with main compressor intercooling, in which an intercooler is added between the two main compressor stages; and 4) a recuperated, recompression cycle with both reheat and main compressor intercooling. All the power plants analysed were 550 MWe (net) in size, and designed to capture over 95% of CO_2. The TIT for the sCO_2 turbine was 620°C, which is comparable to the conditions used in the ultrasupercritical steam cycle (in this study, steam conditions of 24.1 MPa/593°C/593°C were used for the analysis). Cycle 4 (recompression with reheat and intercooling) was also analysed at an elevated TIT of 760°C. The results (shown in Figure 23) indicated that the reference steam plant and the baseline sCO_2 Brayton plant had a similar performance; the steam plant has a modestly higher (0.3% points) process (that is, overall plant) efficiency (HHV based). The use of reheat and main CO_2 compressor intercooling, and a combination of the two, all led to significant increases in the efficiency. When reheat and intercooling were used together, the increase in power cycle efficiency was almost equal to the sum of the increases observed from using reheat and intercooling singly. At the higher TIT of 760°C, cycle efficiency increased to 53.8% compared to 49.4% at a TIT of 620°C. The process efficiency increased by 4.1% points from 35.2% to 39.3%, which is almost the same gain as for the cycle efficiency.

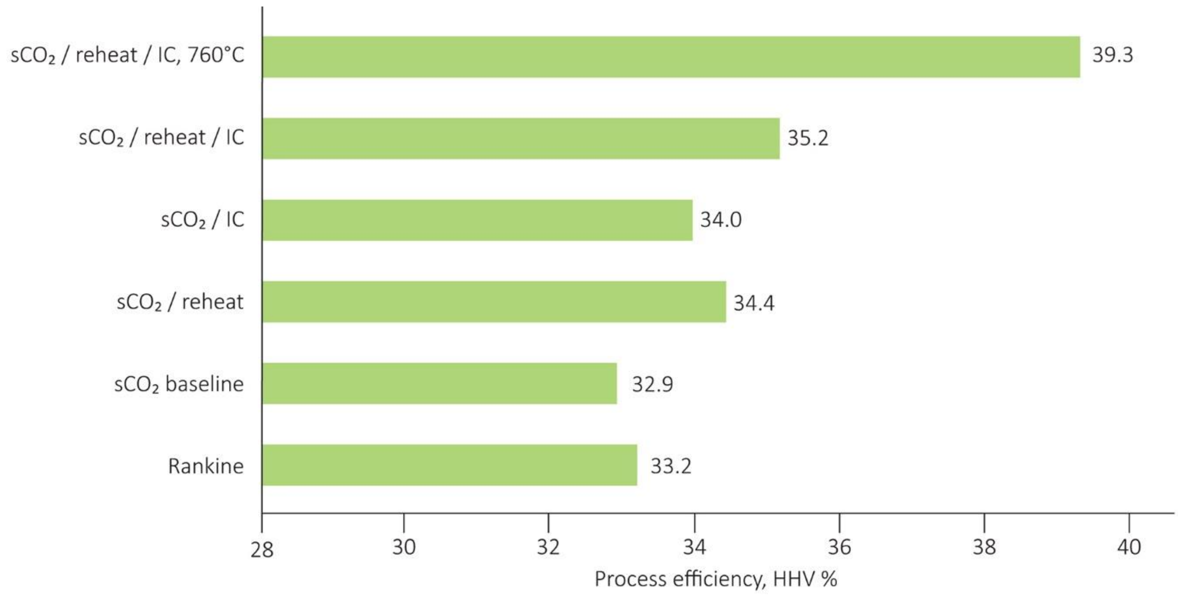


Figure 23 Efficiency comparison of coal oxyfired ACFB power plants with Rankine cycle and with closed-loop sCO_2 Brayton cycles (Shelton and others, 2016)

More work is needed to identify the optimum sCO_2 cycle configurations for coal power. In general, recuperated, recompression sCO_2 cycles are often chosen for fossil fuel application investigations.

Recently, researchers at GE Global Research and SWRI developed conceptual designs of the thermodynamic cycle and key components (turbines, compressors and recompressors) for a 50 and 450 MWe (net) sCO_2 coal power plant. The technology gaps and key issues to be addressed were discussed in detail. System simulations were used to determine the optimum cycle and component designs. A simple recompression cycle was selected for the 50 MWe plant and a reheat recompression cycle for the 450 MWe plant. The major differences between the 50 and 450 MWe cycles were that, a HPT and a LPT are used and a reheater was added between the HPT and LPT for the 450 MWe design. The turbine design of the 50 MWe plant is a scaled-up version of the 10 MWe axial turbine technology developed for CSP discussed in Section 3.2.1. The 450 MWe sCO_2 turbine design is based on the same technology but modified to have an assembled rotor with a dual-flow layout for both the HPT and the LPT. The HPT and LPT are housed in a single casing and supported on a single bearing span. Analyses showed that the 50 MWe sCO_2 power cycle could achieve a thermal efficiency of 49.6% whilst the 450 MWe cycle could achieve a cycle efficiency of 51.9% (Bidkar and others, 2016a,b).

Muto and colleagues (2010) developed a conceptual design of a 300 MWe fossil-fuel fired sCO_2 cycle power plant. A recuperated, recompression cycle with intercooling, precooling and a double expansion turbine was adopted. The configuration is shown in Figure 24, and Figure 25 shows the energy flow diagram for the system. Fossil fuel is burned in air at atmospheric pressure. The heat energy of the combustion gas is transferred to sCO_2 in a CO_2 heater. The flue gas exits the CO_2 heater at temperatures between 400–500°C and this heat energy is recovered in an economiser. A high-pressure and a low-pressure turbine are used on each side of the CO_2 heater, as shown in Figure 24. The sCO_2 from the high temperature recuperator enters the high-pressure turbine at a TIT of around 560°C and 20 MPa. The expanded sCO_2 then enters the CO_2 heater at a temperature of around 448°C and pressure of 8 MPa, and is heated to 650°C before it is used to drive the low-pressure turbine. With this arrangement, the pressure difference in the CO_2 heater between the gas side and sCO_2 side is significantly reduced making the structural design of the heater much easier. With the maximum cycle temperature of 650°C, the cycle can achieve a thermal efficiency of 43.4%.

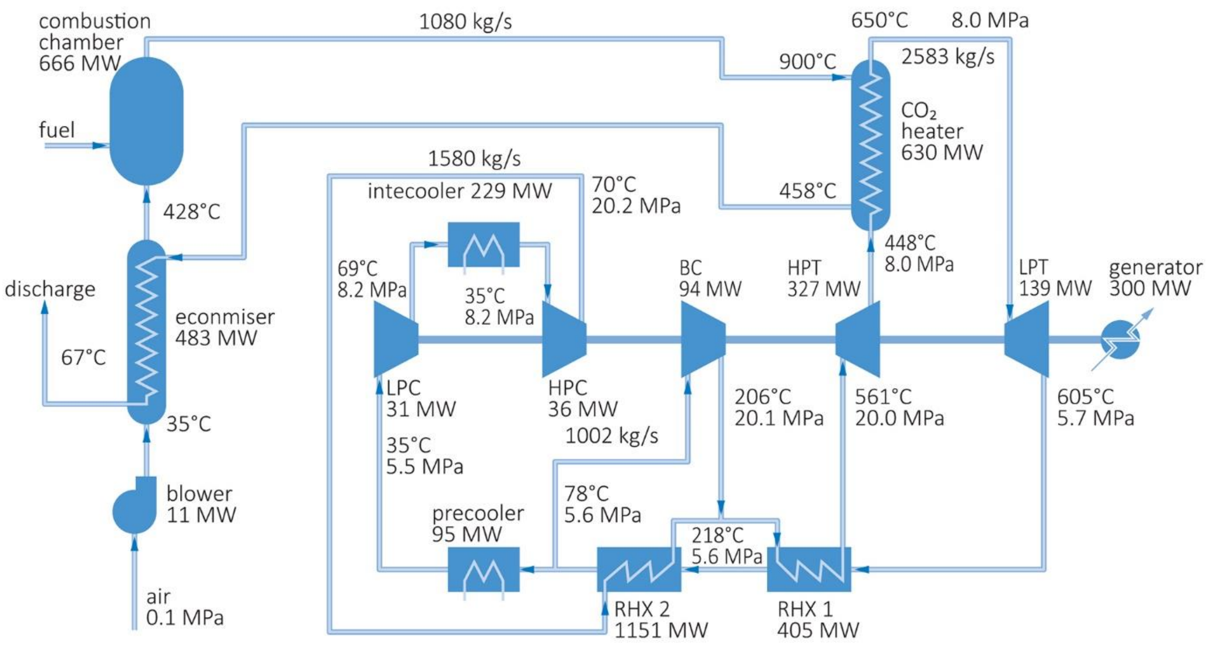


Figure 24 The layout of the 300 MWe fossil-fired sCO_2 cycle power plant (Muto and others, 2010)

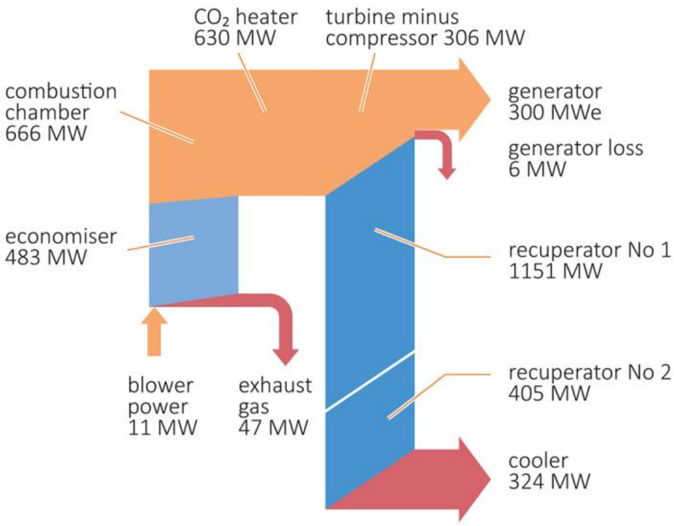


Figure 25 Energy flow diagram of the system (Muto and others, 2010)

A different conceptual design of coal-fired sCO_2 cycle power plant with CO_2 capture was developed at EDF R&D. Figure 26 shows the sCO_2 cycle adopted and a block flow diagram of the coal-fired sCO_2 cycle power plant. The power cycle has been adapted to the coal-fired boiler thermal output. Analyses indicate that the designed sCO_2 cycle coal power plant without carbon capture could achieve a net efficiency of 50% (LHV) with maximum temperature and pressure of 620°C and 30 MPa. A net power plant efficiency of 41.3% (LHV), with 90% post-combustion CO_2 capture, is achievable using available or close-to-available carbon capture technologies (Le Moullec, 2013).

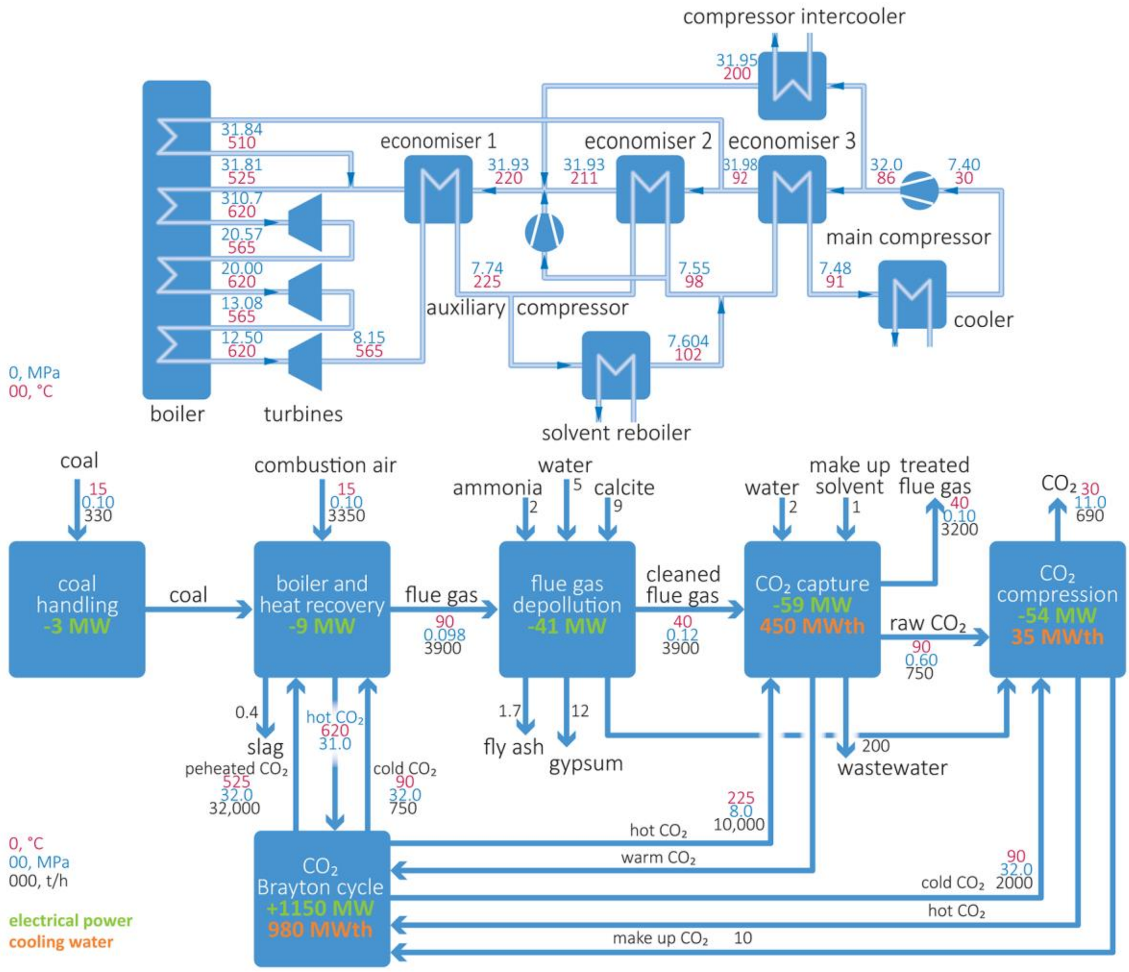


Figure 26 sCO_2 power cycle adapted for coal-fired boiler with carbon capture (top) and a simplified block flow diagram of the power plant built around a sCO_2 Brayton cycle (bottom) (Le Moullec, 2013)

Aerojet Rocketdyne (USA) assessments did not reveal efficiency benefits in recompression closed sCO_2 cycles over a steam Rankine cycle with single reheat at TIT of <535°C. However, due to the smaller turbomachinery sizes and lower costs of compression, they could offer lower operating and maintenance costs, and so a potentially lower cost of electricity. The LCOE for a pressurised fluidised bed (PFB) oxy-combustion boiler coupled with a recuperated, recompression closed sCO_2 cycle with TIT of 704°C was compared with those of two of NETL's baseline plants B12A (SCPC) and B12B (SCPC with post-combustion CO_2 capture) (*see* Figure 37). The differences in efficiency, and hence fuel costs, are small between the three cases. However, the capital and operating costs of the post-combustion carbon capture system are high. The predicted capital cost of the SCPC with CCS is 37% higher than that of a SCPC and 26% higher than the predicted cost of the PFCB oxy-combustion sCO_2 power plant with CO_2 capture. The LCOE of the PFCB oxy-combustion sCO_2 power plant with CO_2 capture was estimated to be 18% higher than that of SCPC baseline plant meeting the 35% target increase set by the US DOE by a considerable margin (Eastland and others, 2014; Huang and Sonwane, 2014).

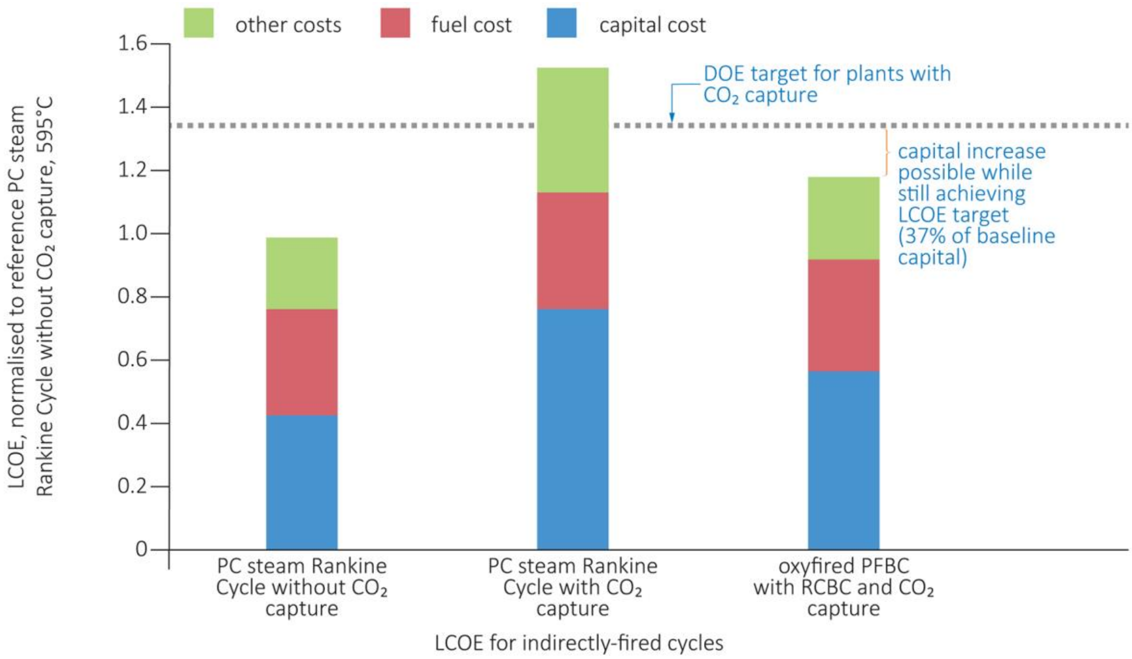


Figure 27 Comparison of LCOE of PCFB closed sCO_2 power cycle plant with NETL baseline plants (Eastland and others, 2014)

5.1.2 Directly-fired semi-closed sCO_2 cycles

A directly-fired oxy-combustion sCO_2 cycle proposed by NETL is illustrated in Figure 27. In this cycle, gaseous fuel is burned in oxygen and the resulting steam/CO_2 mixture is used to drive the turbine. The remaining heat in the steam/CO_2 mixture is recuperated to preheat the cooled and compressed CO_2 that is used as the combustion diluent. The mixture is further cooled to condense the water out and then compressed for CO_2 storage (NETL, 2017).

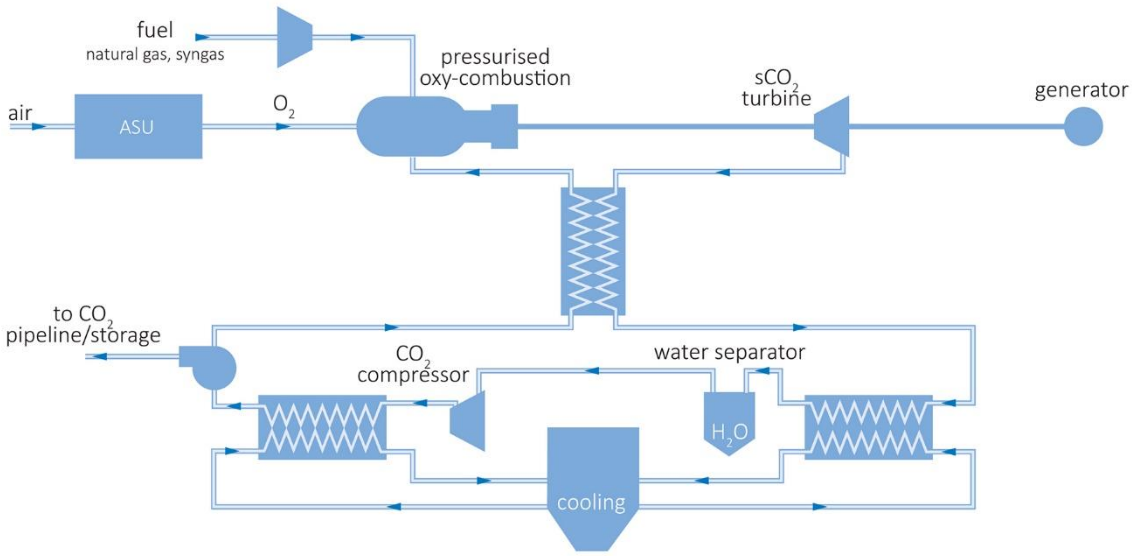


Figure 28 A potential configuration of oxygen-fuelled directly-heated sCO_2 cycle (NETL, 2017)

Working with Thar Energy, SWRI proposed a directly-fired, oxy-combustion semi-closed sCO_2 power cycle for coal. Two approaches using coal syngas fuelling were examined: the cryogenic pressurised oxy-combustion cycle (CPOC) and the advanced supercritical oxy-combustion cycle. The CPOC is a transcritical CO_2 power cycle (that is, the pressure of the CO_2 in part of the system falls below the critical pressure), while the advanced supercritical oxy-combustion cycle is based on the recompression cycle, with supercritical pressures maintained throughout. The analyses showed that the CPOC with recuperation held promise. At a TIT of 1200°C, it could achieve a cycle efficiency similar to that of a recompression closed sCO_2 Brayton reference cycle while having a reduced recuperation requirement and lower combustor inlet temperature (McClung and others, 2015, 2014).

The cycles were examined against the target goal of 90% CO_2 capture at ≤35% increase in cost of electricity (COE) as compared to a supercritical pulverised coal (SCPC) plant without CO_2 capture. For comparison, an indirect supercritical oxy-combustion unit coupled with a recompression closed sCO_2 cycle power block integrated with CCS was developed that provided 99% carbon capture. In this configuration, the power block achieved 48% thermal efficiency for turbine inlet conditions of 650°C and 29 MPa. Higher power block efficiency was achieved at higher TIT. However, a design trade-off was made to limit firing temperatures to 650°C. These meant austenitic stainless steels could be used for the high temperature pressure vessels and piping and the need for advanced turbomachinery features such as blade cooling could be minimised. Initial evaluations showed that, with a similar level of component maturity, the CPOC cycle achieved 38% thermal efficiency for reasonable loop pressures compared to ~47% at 650°C and 29 MPa attained by the recompression closed cycle. The performance of CPOC could be improved significantly by incorporating recuperation. Further evaluation of the CPOC showed that the efficiencies of recuperated CPOC exceeded that of the recompression cycle even at lower temperatures, and at a firing temperature of 1200°C, thermal efficiencies for both the Recuperated CPOC and the recompression cycle could achieve 63% (McClung and others, 2015, 2014).

EPRI (2014) compared the performance and economics of syngas-fired direct sCO_2 cycles based on coal gasification with a conventional integrated gasification combined cycle (IGCC), both using a slagging, entrained flow gasifier with the gas turbine and heat recovery steam generator replaced by the sCO_2 power cycle. The sCO_2 cycles incorporated virtually full CO_2 capture. A steam bottoming cycle was retained to generate power using heat recovered from syngas cooling. Three variants were examined:

Case 1) conventional nitrogen for the coal transfer fluid;
Case 2) replacing the nitrogen with recycled CO_2 gas;
Case3) recycled CO_2 gas for coal transfer fluid and improving oxygen purity levels used by the plant.

These variations were selected in order to understand the impact of impurities on the power cycle and the changes incurred by the gasification process as a result of steps to reduce impurities.

Results are shown in Table 3. The power output from the sCO_2 cycles almost matched that from the reference IGCC, achieving a plant thermal efficiency of 39.6% with >99% CO_2 capture compared to 40% for the IGCC reference plant with no capture or 31.1% efficiency with 87% CO_2 capture. High oxygen purity (99.5%) and CO_2 as coal transfer carrier gas were required to achieve storage-ready CO_2 purity (98.1%). The capital costs were 38% higher than for the IGCC plant with carbon capture but comparable on a specific

(US$/kW) basis, at approximately 4700 US$/kW. The levelised cost of electricity (LCOE) was also similar, at 133 US$/MWh for the sCO_2 power plant and 138 US$/MWh for the original IGCC plant with capture, which was ~39% higher than the baseline non-capture case at 97.5 US$/MWh (Hume, 2016; EPRI, 2014).

Table 3 Performance comparison of IGCC reference plant and sCO_2 cycles (Hume, 2016)

	IGCC w/o capture	sCO_2 Case 1	sCO_2 Case 2	sCO_2 Case 3
Transfer fluid	N_2	N_2	CO_2	CO_2
Oxygen purity, (volume)%	95	95	95	99.5
Fuel input, MWth	1470	1470	1470	1470
GT/expander power output, MWe	464	922	864	846
Steam turbine power output, MWe	235	52.3	58.4	59.3
CO_2 compression, MWe		95.0	86.3	83.2
CO_2 pumps, MWe		113.6	87.2	72.4
Fuel compression, MWe		46.6	43.4	42.7
Oxygen supply (ASU/Compression), MWe	74.4	91.1	90.7	92.5
Gasifier auxiliary, MWe	16.2	16.2	16.2	16.2
Plant auxiliary, MWe	19.3	14.7	14.9	14.8
Net power exported, MWe	587.9	596.0	582.4	582.6
CO_2 emission, g/kWh	803	5.3	6.9	6.2
CO_2 product purity, (volume)% wet		80.1	93.2	98.1
Overall plant efficiency, % (HHV basis)	40.0	40.5	39.6	39.6
CO_2 capture rate, %		99.5	99.3	99.2

Similar work was conducted at NETL. Shell's dry-feed, pressurised, oxygen-blown entrained-flow gasifier was selected and Illinois No 6 bituminous coal assumed for this study of a 600 MWe (nominal) plant. The configuration is shown in Figure 31. The parameters used for analysis of the baseline sCO_2 power cycle are given in Table 4. An IGCC with hydrogen turbine and carbon capture was used as the reference plant. The gasifier island and gas clean-up sections in the IGCC were similar for both plant types except that the IGCC plant utilised an elevated pressure cryogenic ASU to produce 95% purity oxygen. In the sCO_2 plant, the ASU was a low-pressure unit and produced 99.5% purity oxygen to minimise argon and nitrogen contaminants in the sCO_2 cycle. The IGCC plant used nitrogen as the transport gas for the dry feed lock hopper system, whereas the sCO_2 plant uses CO_2, as in the EPRI study.

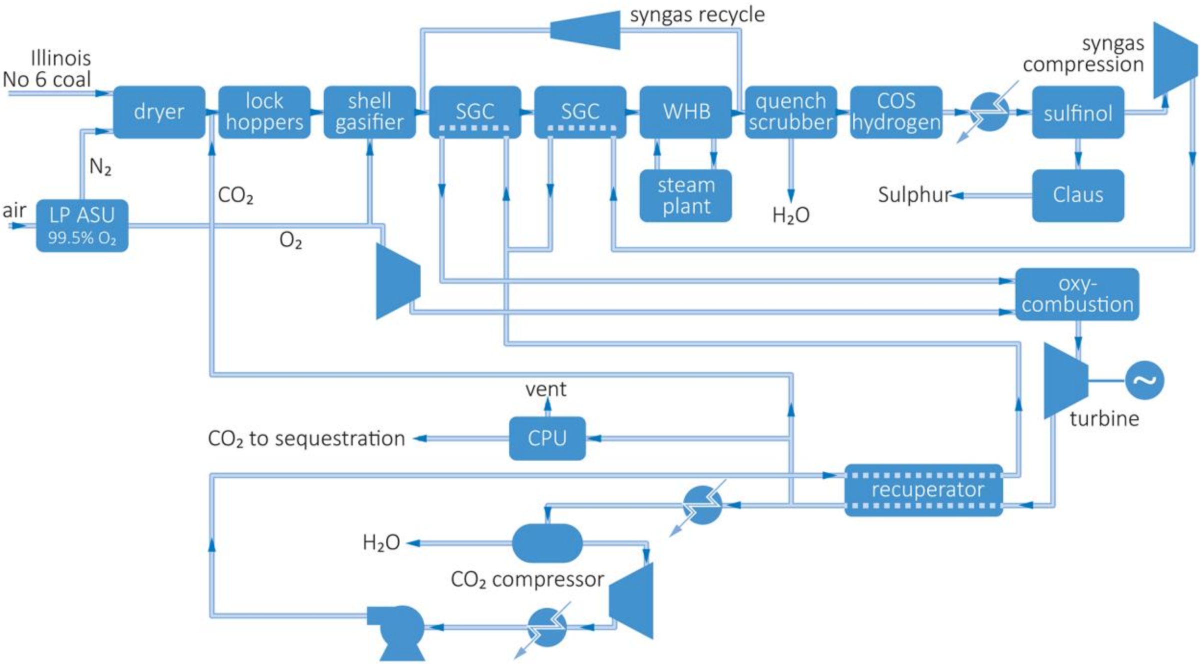


Figure 29 Block flow sheet of the syngas-fired, semi-closed oxy-combustion sCO_2 power plant (Weiland and others, 2016)

Table 4 Baseline parameters of the sCO_2 power cycle used in NETL's analyses (Weiland and others, 2016)

Parameter	Value
Heat source	Pressurised oxy-syngas combustor
Cycle thermal input	1315.0 MWth
Turbine exit pressure	3 MPa
Cooler exit temperature	27°C
Turbine inlet temperature	1149°C
Turbine isentropic efficiency	92.7%
Compressor isentropic efficiency	85%
Recuperator maximum temperature	760°C
Recuperator pressure drop per side	0.14 MPa
Combustor pressure drop	0.07 MPa
CO_2 cooler pressure drop	0.14 MPa
Minimum recuperator temperature approach	10°C
Nominal compressor pressure	30 MPa
Nominal compressor pressure ratio	11.0

The analyses for these non-optimised cycles showed a net power output of 562.6 MWe and net plant thermal efficiency of 37.7% (HHV), for the direct-sCO_2 plant with 98.1% CO_2 capture at 99.4% purity. The reference IGCC plant had a 496.9 MWe net power output, 31.2% (HHV) net thermal efficiency, and 90.1% CO_2 capture rate at 99.99% purity. Thus, the sCO_2 plant generated almost 13% more power and required

6% less coal than the IGCC plant. Sensitivity analyses showed that intercooling was a particularly effective option for further improving cycle and plant efficiency (Weiland and others, 2016).

5.2 Allam Cycle

5.2.1 Allam Cycle description

R&D is most advanced on the Allam Cycle, a semi-closed, recuperated, oxy-combustion transcritical CO_2 power cycle for fossil fuel power generation. Here, the pressure of the CO_2 exiting the turbine is below the critical pressure of CO_2. The core process is a gas-fired cycle, with an inlet pressure of approximately 30 MPa. A simplified schematic of the Allam Cycle configured for coal syngas firing is shown in the orange area in Figure 28. A pressurised gaseous fuel is burned in the oxy-combustor at approximately 30 MPa in a mixture of O_2 and recycled CO_2. The exhaust from the combustor is expanded through a turbine to approximately 3 MPa, decreasing in temperature to >700°C. Following the turbine, the exhaust flow enters a recuperator where it is cooled to around 60°C by transferring heat energy to the high-pressure CO_2 recycle stream that acts as a diluent to control the combustion temperature and maintain the TIT at a desired 1150°C. The gases are further cooled to near ambient temperature, at which any water contained in the flue gas is condensed and separated, resulting in a stream of predominantly CO_2. The CO_2 stream is compressed to the high pressure required and is then split into three. The first portion is mixed with high pressure oxygen to form the oxidant stream. The second portion, comprising the majority of the CO_2 flow, forms the recycle CO_2 stream. Both the oxidant stream and the recycle CO_2 stream are pumped to 30 MPa and heated in the recuperator to >700°C before being injected into the combustor. The third part of the CO_2 stream is exported via pipeline for storage or utilisation. This net export is approximately 5% of the total recycle flow, meaning most of the process inventory (95%) is recirculated (Lu, 2017; Allam and others, 2013; 2016).

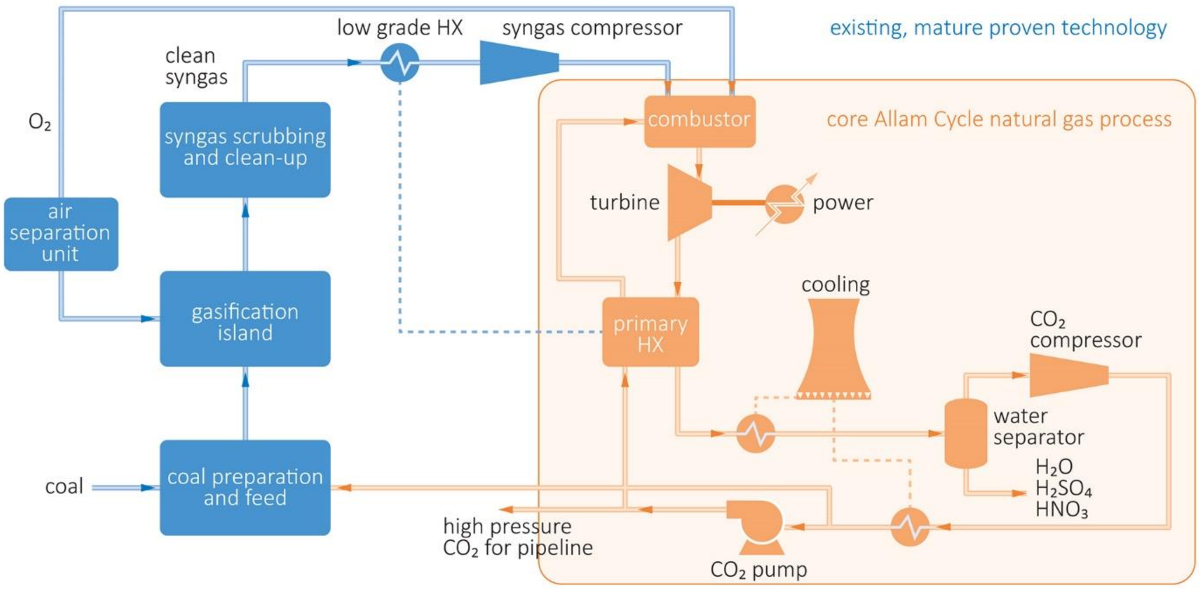


Figure 30 A simplified block flow diagram of the Allam Cycle couple with a coal gasification system (Lu, 2016)

The optimum high pressure for operation of the system is between 20 and 40 MPa, while the optimum pressure ratio is in the range of 6 to 12. This means that the CO_2 recycle compressor inlet pressure will be below the CO_2 critical pressure of 7.4 MPa so that it requires initial compression in a conventional, multi-stage, inter-cooled compressor to about 8 MPa. The supercritical CO_2 is then cooled to near ambient temperature in the compressor after-cooler, then compressed to the pressure required using a multi-stage centrifugal pump.

Due to the large difference between the specific heat of the recycle CO_2 (30 MPa) and the turbine exhaust CO_2 (3 MPa) at the low temperature end of the recuperator, there is a significant imbalance between the heat liberated by the low-pressure turbine exhaust and the heat required to raise the temperature of the high pressure recycle stream. External heat is required to make up for this which can be met by heating the high-pressure recycle CO_2 stream with low grade heat at 100-400°C. A convenient source of heat can come from the adiabatic operation of the ASU's air compressors and the recycle CO_2 compressor. Although this increases the compressor power, the overall effect on efficiency is positive.

The turbine inlet temperature, hence efficiency, is limited by the maximum allowable temperature (700–750°C) of the turbine exhaust entering the hot end of the recuperator. The maximum allowable temperature is determined by the operating pressure of the recuperator and the properties of the construction materials. This leads to a typical TIT constraint in the range of 1100–1200°C (Lu, 2017; Allam and others, 2013; 2016).

Under development for over seven years by 8 Rivers Capital (USA), the Allam Cycle can use a variety of hydrocarbon fuels including natural gas and syntheses gas (syngas) derived from gasification of coal, oil refining residuals and biomass with target net efficiencies of 50% (LHV) for coal and of 59% (LHV) for natural gas, and full carbon capture.

5.2.2 Natural gas-fuelled Allam Cycle power plant demonstration

NET Power is currently building a 50 MWth (25 MWe) natural gas demonstration power plant in La Porte, Texas (USA), scheduled for operation in early 2018. The aim is to demonstrate the characteristics of the cycle and verify the design and operation of the integrated power generation system and individual components. Process design has been developed by 8 Rivers Capital, with engineering, procurement and construction by CB&I. The plant will be operated by Exelon. Oxygen will be supplied from an Air Liquide facility. The plant will be connected to the grid. The demonstration process will match the operating conditions of the core Allam Cycle and the expected commercial temperatures and pressures. Tests will be carried out to validate performance, control methodology and component durability. There will be full evaluation of cycle operability including start-up, shut-down, load following, emergency operations and partial-load operation, as well as reliability and safety.

The plant uses equipment already proven except for the turbine and combustor. NET Power has been working with Toshiba, which is developing and supplying the turbine. As discussed in Section 4.2.1, the turbine for the demonstration plant has already been shipped to the site together with its generator and auxiliary equipment. Through successful operation of a 5 MWth test unit (*see* Section 4.2.4), Toshiba has developed the high-pressure combustor, which attained the required maximum test pressure of 30 MPa in 2013. The demonstration combustor was shipped in early 2017 and is being tested before being commissioned as an integrated part of the combustion turbine assembly. The main CO_2 recycle compressor is coupled to the turbine rotor shaft to allow the compressor to limit turbine over-speed in the event of load disconnection. The seal of the turbine shaft leaks a portion of the recycling CO_2, which can be recovered, recompressed to 3 MPa and returned to the cycle (Iwai and others, 2015).

Heatric's diffusion bonded PCHEs are used in the demonstration plant. Each heat transfer plate is 1.6 mm thick with flow channel patterns optimised for the application. The heat transfer system comprises a four-stage high-pressure, high-temperature recuperator for the main process stream and the separate recycle CO_2 compressor aftercooler. The staged HE design enables the bulk of the heat transfer surface to be manufactured from cheaper materials, minimising the use of expensive superalloys, which are used only for the hottest section. The high temperature section operates in a temperature range of 550–700°C and is fabricated from 617 alloy to withstand the required operating temperature under 30 MPa pressure. The remaining three sections operate at temperatures lower than 550°C and are constructed from 316L stainless steel (Allam and others, 2016).

A full-scale, 300 MWe gas-fuelled Allam Cycle commercial plant is currently in the design phase. A pre-FEED (front end engineering design) study has been completed, and the FEED and early development work have begun. The commercial plant will incorporate modular design concepts where possible and will be optimised for performance and cost. Lessons learned from the demonstration plant will be incorporated into the commercial plant design throughout the completion of construction, start-up and testing of the demonstration facility. Toshiba is undertaking the design of the commercial-scale combustion turbine. Several commercial partners are already engaged and potential sites for the plant are being vetted. NET Power aims to put the first commercial Allam Cycle power plant in operation in 2021 (Allam and others, 2016; Lu and others, 2016; Lu, 2017).

5.2.3 Allam Cycle for coal power

In parallel to the development of the natural gas-fuelled Allam Cycle with NET Power, 8 Rivers Capital is developing a coal-based system (shown in Figure 28), fuelled with cleaned syngas from a commercially available oxygen-blown gasifier.

Gasification process

The selection of an appropriate gasification process is dependent primarily on the type of coal to be used but additional considerations for this application include:

- *Coal preparation and feed*: an Allam Cycle coupled with a slurry-feed gasifier with water quench cooling would provide a simple process that has the lowest capital cost with high reliability. The high gasification pressure achievable will reduce syngas compression energy, offsetting the lower cold gas efficiency compared to dry-feed gasifiers. Where a dry-feed gasification process is required (for instance with high-moisture, high-ash coals) or is preferred for fuel flexibility, integration with the Allam Cycle will favour use of CO_2 as the carrier gas (instead of N_2 that is commonly used) for the feed system.

- *Gasification process*: three major types of gasifier are commercially available – moving bed, fluidised bed and entrained-flow, each with its own cold gas efficiency (CGE) and syngas composition, temperature and pressure. The primary factor to consider is the CGE, but it is also important that the syngas is free of entrained particulates and heavy hydrocarbons to avoid fouling and plugging of equipment such as the microchannel HE.
- *Syngas cooling*: full water quench cooling provides several advantages as discussed above. Most of the ash in the syngas is also removed during the quenching process. The gas stream after quench cooling has a temperature typically ranging from 200°C to 300°C and is saturated with moisture. The system thermal efficiency can be maximised if the heat energy of this stream can be recovered and transferred into the Allam Cycle.

Pre- and post-combustion clean-up

Fine particulates must be removed before the syngas enters the combustion turbine. Several existing technologies can fill this role. Upon exiting the gasifier, the syngas passes through an additional water scrubber and a fine particulate removal device. The syngas, at a temperature of 175–260°C and 3–4 MPa pressure, is then cooled to near ambient temperature. This cooling condenses the steam content for removal to increase the heating value of the syngas. The thermal energy can be recuperated by heating the high-pressure CO_2 stream in the low temperature region, or by heating a closed-loop intermediate pressure water stream. The latter design simplifies the design of the heat exchanger by avoiding the use of the high-pressure streams. In addition, recuperation can be done by heating nitrogen from the ASU to around 100°C for coal drying.

8 Rivers Capital is working on a post-combustion syngas cleaning process called DeSNOx for SOx and NOx removal. After removal of fine particulates and cooling, the predominant impurities in the turbine exhaust stream are SO_2, NO and NO_2. In the water separator (see Figure 28), which is a direct contact cooler (DCC), the flue gas, at approximately 3 MPa and in the temperature range 66–93°C, comes into direct contact with the water. The NOx and SOx in the flue gas are removed via reactions constituting a version of the Lead Chamber Process. Earlier studies showed that approximately 99.9% SO_2 removal and 80% NOx removal could be achieved in continuous operation. An assessment of the potential corrosion problems using this approach is ongoing, with a particular focus on the lower temperature regions of the plant where water condensation and hence, acid precipitation may occur (Lu, 2016; Allam and others, 2016).

Pre-combustion acid gas removal (AGR) processes have also been investigated for comparison. Although more costly, such systems have potentially lower technology risks and less corrosion concerns. Cycle analyses showed that the DeSNOx process gave the higher cycle efficiency (~3% points) (Fetvedt and others, 2014; 8 Rivers Capital/EPRI, 2014; Lu and others, 2016).

Turbine and combustor

Analysis showed that because of similar working fluid chemistries, with the same temperature and pressure range applied, the sCO_2 turbine developed for the natural gas Allam Cycle could be applied to the clean coal gas fuelled Allam Cycle. However, the change from natural gas to syngas would necessitate substantial modifications to the combustor. Due to the low heating value of syngas, the volumetric flow rate of syngas to the combustor will be 300% that of natural gas for a given thermal input, necessitating changes to of fuel and oxidant nozzles. The design changes to injection arrangements for the recycled CO_2 are minor because of the large amount of recycling in the Allam Cycle (Lu and others, 2016).

5.2.4 Assessments of the Allam Cycle

8 Rivers Capital conducted comprehensive analyses to optimise the performance of the coal-based Allam Cycle. Two different feedstocks and three major gasifier systems were modelled. All the gasification systems were oxygen blown utilising an oxygen purity of 99.5% provided by an onsite cryogenic ASU. For dry-feed systems, coal drying and CO_2 (instead of N_2) transport gas was assumed. The post-combustion flue gas clean-up system DeSNOx process was used for the analysis. Coal thermal input was 550–650 MWth. The types of coal and gasification processes selected for the evaluations are shown in Table 5 and the results are compared in Figure 32. The figure shows that the net efficiency of the coal-based Allam Cycle power system, with inherent CO_2 capture, ranges from 43.3–49.7% (HHV) depending on the coal and gasification process used. This compares favourably with those of NETL's (2015a,b, 2011) baseline IGCC and SCPC power plant fuelled with bituminous coal or lignite, with or without carbon capture, as shown in Figure 33. The NETL IGCC baseline plant employs similar feedstock and identical gasifiers to the Allam Cycle Case 1. The net plant efficiency of Allam Cycle Case 1 with almost full carbon capture is 18.5% points higher than the IGCC baseline plant with 90% carbon capture. In all six cases analysed, the Allam Cycle out-performed the baseline SCPC and IGCC power plants with or without carbon capture. It was also estimated that a coal-based Allam Cycle would provide water savings of 50–60% compared to the IGCC baseline not employing carbon capture and with lignite feedstock (Lu and others, 2016).

Table 5 Coal type, gasification process and operation selected for Allam Cycle analyses (Lu and others, 2016)

	Case					
	1	**2**	**3**	**4**	**5**	**6**
Coal type	**Bituminous**	**Lignite**	**Bituminous**	**Lignite**	**Bituminous**	**Lignite**
Gasifier type and operation	Entrained flow, dry-feed	Moving bed	Entrained flow, dry-feed	Entrained flow, dry-feed	Entrained flow, slurry	Fluidised bed
	Slagging	Slagging	Slagging	Slagging	Slagging	Non-slagging
Heat recovery scheme	Syngas cooler	Full water quench	Full water quench	Full water quench	Syngas cooler	Syngas cooler

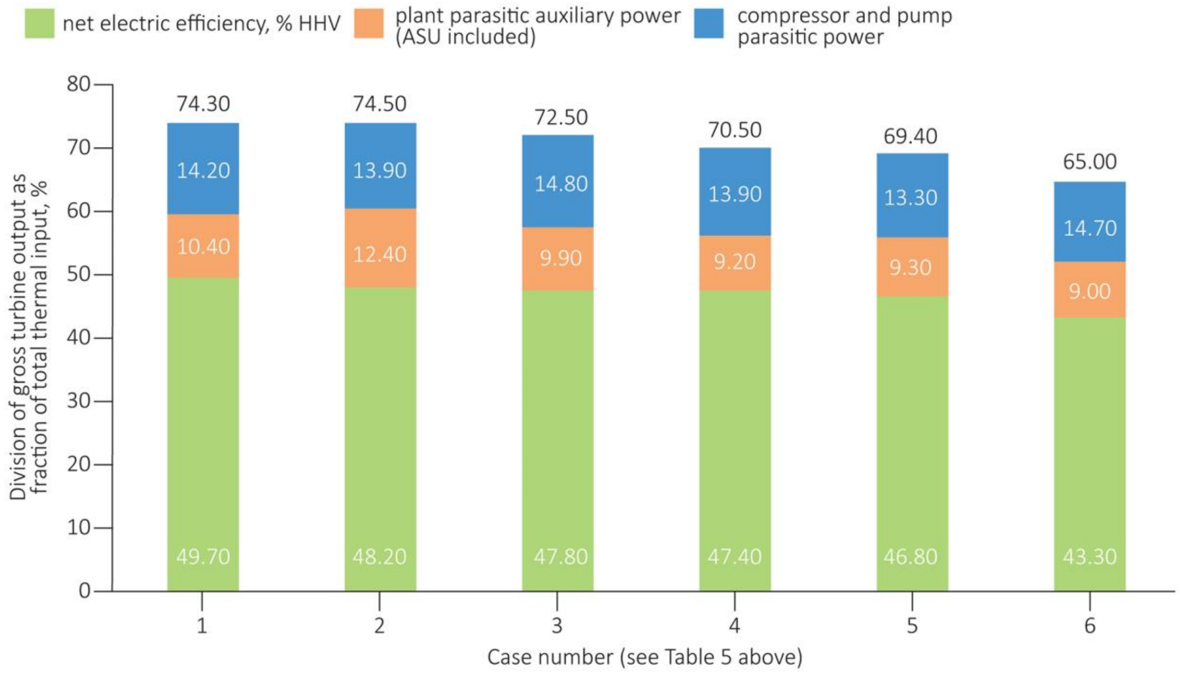


Figure 31 Comparison of optimised coal Allam Cycle configurations (Lu and others, 2016)

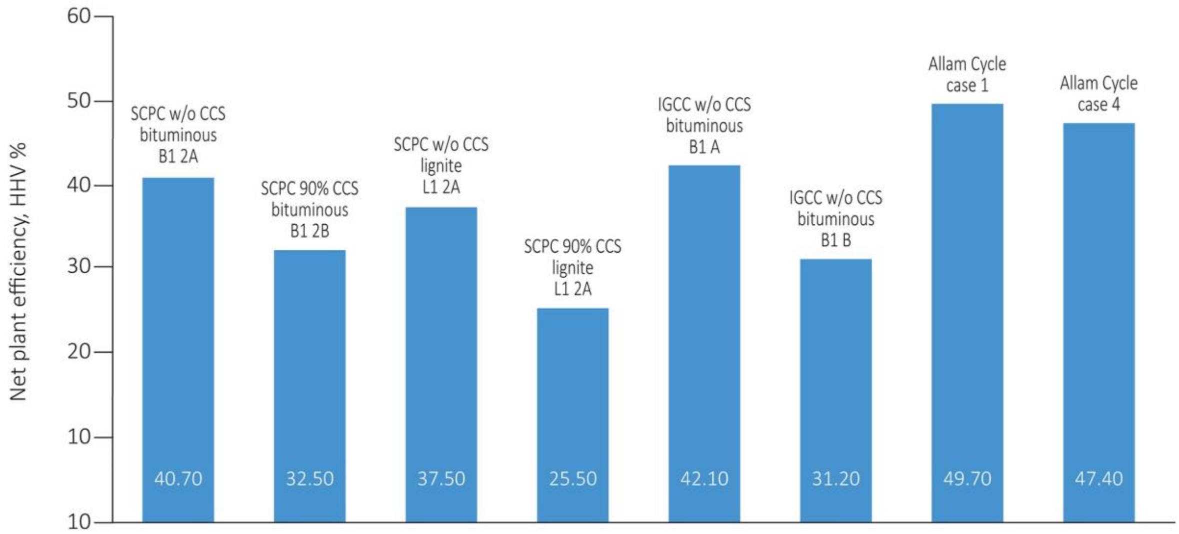


Figure 32 Comparison of coal-based Allam Cycles with NETL baseline plants

A preliminary economic analysis indicated that an Allam Cycle with full carbon capture would be competitive with existing SCPC and IGCC plants without carbon capture. The LCOE of different power cycles with and without CCS are compared in Figure 34 (Allam and others, 2013; Lu, 2016).

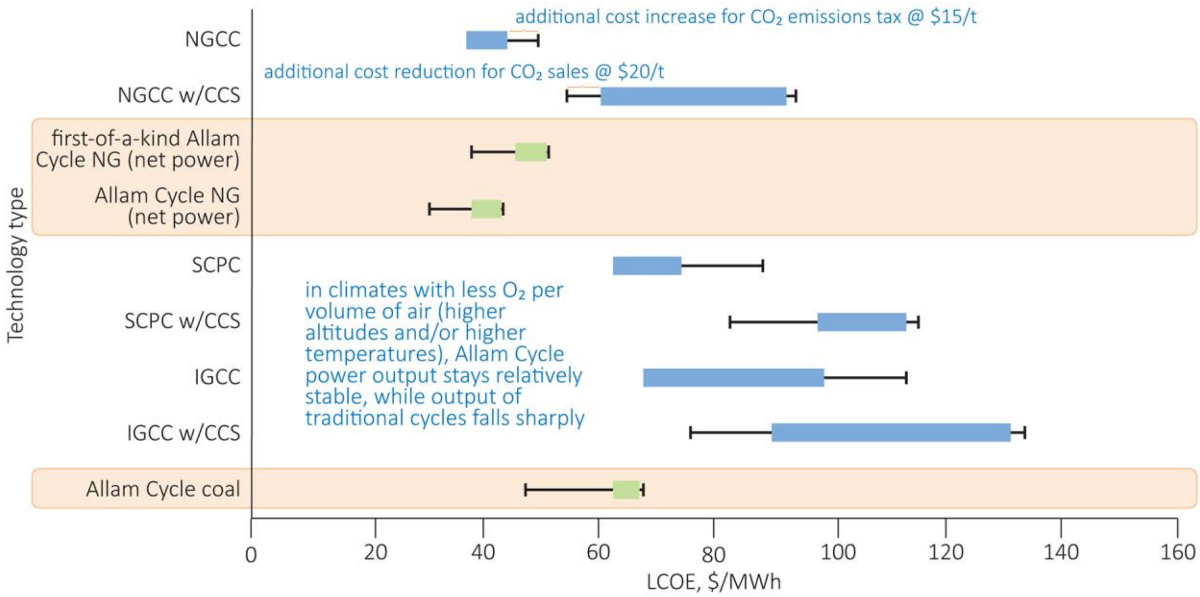


Figure 33 Costs comparison between Allam Cycle and existing power cycles (Lu, 2016)

Recently, Amec Foster Wheeler (UK) in collaboration with Politecnico di Milano (Italy) conducted a comprehensive evaluation of the performance and costs of a range of natural gas-fuelled oxy-combustion turbine cycles, mainly for utility-scale power generation. The power cycles analysed include the supercritical, semi-closed oxy-combustion combined cycle (SCOC-CC), Allam Cycle, S-Graz cycles and Clean Energy Systems (CES) and a conventional gas-fired combined cycle (NGCC) was used as a reference plant. This work was carried out on behalf of the IEA Greenhouse Gas R&D Programme (IEAGHG). Using slightly different assumptions, it found that a gas-fuelled Allam Cycle could achieve a thermal efficiency of 55.1%, compared to 52% for an NGCC with post-combustion capture or 58.8% for an NGCC without CCS. This was around 6% points higher than the other oxy-combustion power cycles analysed. The main results are shown in Table 6 (IEAGHG, 2015). The Allam Cycle had a slightly lower LCOE than a conventional NGCC with post-combustion capture using a proprietary solvent.

Table 6 Performance and costs comparisons of gas turbine combined cycles and Allam Cycle (IEAGHG, 2015)

	Efficiency, % (LHV)	Total plant cost, €/kW	LCOE, €/MWh	CO_2 avoidance cost, €/t
NGCC w/o CCS	58.8	665	62.5	
NGCC & post-combustion capture	52.0	1170	84.7	72
SCOC-CC	49.3	1470	92.8	98
Allam Cycle	55.1	1320	83.6	68

5.3 Echogen heat engine

Echogen Power Systems, in partnership with Dresser-Rand (USA), has been developing indirectly heated waste heat-to-power sCO_2 cycle power generation technology over the past decade. A 15-kW test facility was built and tests were conducted in 2009, to verify the feasibility of the CO_2 cycle and the turbine design, followed by a 250-kW demonstration system, installed in 2010 at the American Electric Power (AEP) Dolan Technology Center in Groveport, OH, USA, and a second system, the EPS5, a 300 kWe, designed for industrial and distributed generation applications. Echogen then built a scaled-up version, EPS100, a 7.5 MWe prototype designed and built to commercial standards. The EPS100 sCO_2 heat recovery cycle is shown in Figure 29.

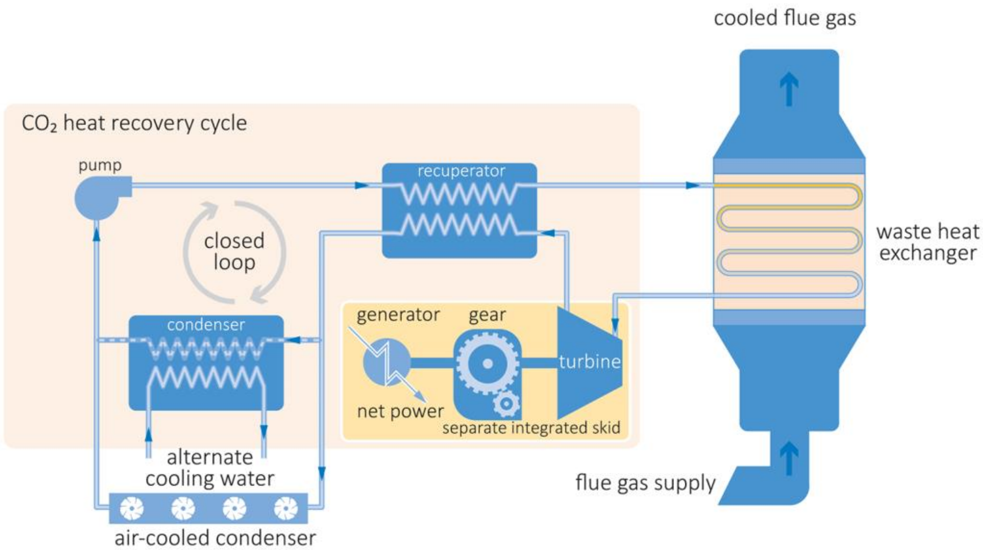


Figure 34 The EPS100 sCO_2 heat recovery cycle (http://www.echogen.com/)

The EPS100 uses a recuperated closed Brayton cycle with multiple stages of recuperation and heat extraction from the primary heat source. Two separate turbines are employed: one, the 'drive turbine' is connected directly to the compressor, while the other 'power turbine' is coupled to a generator for power generation. The power turbine operates at a constant speed, while the turbo-compressor's speed can be varied over a wide range to maintain the optimal flow rate for the fluid loop. Figure 30 shows a simplified cycle layout of the EPS100 test facility. The heat energy of the exhaust stream from industrial processes or gas turbines is recovered through a waste heat exchanger (sCO_2 heater – RC-1) by heating a flow of compressed sCO_2. Downstream of the sCO_2 heater, the heated sCO_2 flow is split into two main streams. Approximately two-thirds of the flow is directed to the power turbine (T2), while the remainder is directed to the drive turbine (T1) for the main sCO_2 compressor. The sCO_2 streams exiting the power turbine and drive turbine pass through recuperators (RC-2) to preheat the CO_2 stream from the compressor before being cooled (in CX-1), compressed and then sent to the sCO_2 heater to complete the cycle. The power turbine has a single-stage radial design. The recuperators and CO_2 coolers are all of the PCHE type, while the sCO_2 heater has a shell and finned tube design.

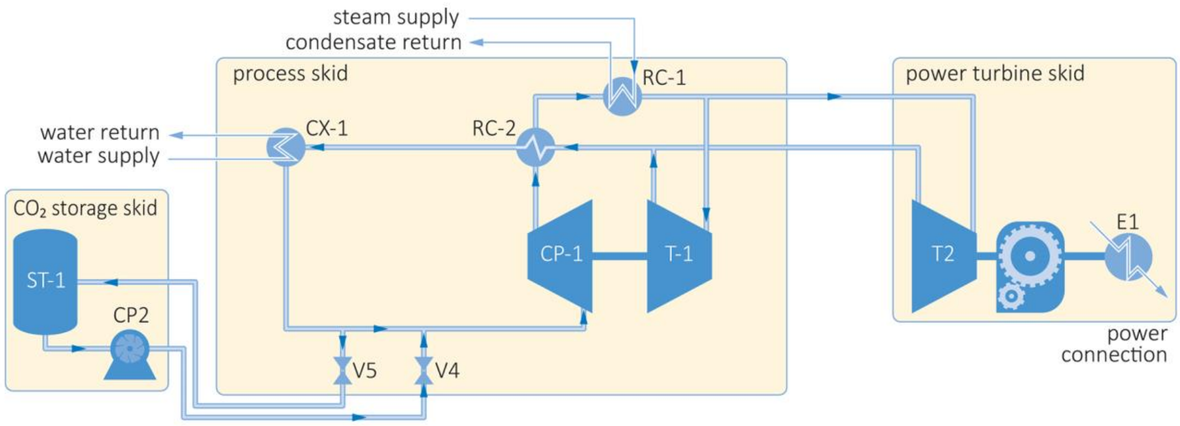


Figure 35 Process flow diagram of the EPS100 test facility (Held, 2014)

The primary control mechanisms for the system are valves (not shown), located at key locations in the process loop. The most important are the compressor bypass valve and turbine throttle valves. In addition, the compressor inlet pressure is actively managed by inventory control, which utilises a separate CO_2 storage tank for supply and withdrawal of fluid from the main process loop as necessary to maintain compressor inlet pressure at the desired value. The operation and control of the EPS100 can be performed centrally and remotely via a proprietary control system and software (Held, 2014).

Tests showed that the full design-point performance of the system met its predicted levels for multiple operating conditions (Held, 2014; Kacludis and others, 2012; Persichilli and others, 2011). Since 2014, the EPS100 heat engine has been offered to the commercial market as a turnkey solution to convert waste heat from various industrial processes to electric power. Echogen Power Systems claim that their heat engines can be applied for industrial waste heat recovery, solar thermal and geothermal power, and as bottoming cycles in gas turbines, stationary reciprocating engine gensets or as hybrid alternatives to the internal combustion engine. Echogen can now provide standard heat engines scalable from 1–9 MWe (net). Based on the EPS100 system, Echogen has also completed a conceptual design of a 10 MWe sCO_2 test facility for the US DOE Nuclear Energy Group. Echogen is currently working with EPRI to develop integrated solutions for coal-fired power plants using sCO_2 power cycles as part of an ongoing US DOE-funded project (www.echogen.com).

Comments

The commercial success of sCO_2 Brayton power cycles will depend on achieving greater overall power plant efficiencies and lower capital costs than conventional plant designs. A number of attractive sCO_2 power cycle designs have been explored over the last decade, but it is unlikely that the optimum power cycle configurations for a given application have been identified at this stage. Nevertheless, sCO_2 cycle power systems are starting to be offered to the commercial market at up to 10 MWe for various low temperature heat sources, though not yet coal. The commercialisation of Echogen's heat engines indicates the technical and economic viability of indirectly-heated, closed sCO_2 cycle power generation systems. The natural gas-fuelled Allam Cycle is now entering the demonstration phase, which will be an important milestone in the development of semi-closed, oxy-combustion sCO_2 power generation systems for fossil fuels. The demonstration will provide insights into the technology's reliability and operability, as well as knowledge and data on the design of utility-scale sCO_2 power cycle equipment. The operation will also provide detailed information on the performance of the cycle and individual components. Coal-fuelled semi-closed oxy-combustion sCO_2 power systems will be more complex and need to overcome additional technical obstacles due to the impurities in coal and the particulates which may cause corrosion, erosion and other problems.

The results from several detailed and extensive analyses indicate that closed Brayton cycles can potentially achieve better performance than other power cycles such as the steam cycle, whilst directly heated, oxy-combustion sCO_2 cycles such as the Allam Cycle have great potential for coal-based power generation. They can potentially achieve high net plant efficiency while producing a stream of high concentration CO_2 ready for transport and storage and could be competitive, both technologically and economically, with a supercritical power plant with post-combustion carbon capture or other advanced power cycles with CCS.

6 Summary and conclusions

The sCO_2 Brayton cycle energy conversion system is an innovative concept that transforms heat energy to electrical energy through the use of supercritical CO_2 as the working fluid. The sCO_2 cycle can potentially reach thermal efficiencies of 50% or more. The high energy density of sCO_2 means the components are small, as is the overall plant footprint. These factors coupled with other technology attributes could potentially result in lower capital and fuel costs and decreased GHG emissions from coal-fired power generation. Two primary sCO_2 power cycle configurations have been reviewed: an indirectly-heated closed Brayton cycle and a semi-closed, directly-fired, oxy-combustion cycle. A closed-loop Brayton cycle operates in a way similar to a steam Rankine cycle but uses sCO_2 as a working fluid. It can be used in essentially any application that currently uses a Rankine cycle including nuclear, solar thermal power, geothermal, waste heat and fossil fuel combustion. The most promising application areas for semi-closed, directly-fired oxy-combustion sCO_2 cycles are in fossil fuel-fired power generation, in particular when carbon capture is required.

Over the last decade, there has been extensive RDD&D worldwide, in particular in the USA. Much of the effort has focused on the development of sCO_2 turbomachinery, particularly on the design and construction methods of heat exchangers and materials testing. In recent years, the US DOE has invested tens millions of dollars to promote the RDD&D of sCO_2 cycle power generation technologies. A six-year project to design, build, and operate a 10 MWe sCO_2 pilot plant test facility has been planned and is funded by the US DOE. R&D of sCO_2 power cycles for application for nuclear, solar, fossil fuel power and low-grade heat sources are also being actively pursued in Australia, Canada, France, Germany, Netherlands, Spain, UK and more recently, China and India. These activities are mostly confined to laboratory-scale testing and computer modelling and analysis.

Recent developments at components level

The fundamentals of engineering tools for steam and gas turbine and compressor design can be used in the designs and manufacture of sCO_2 turbomachinery. However, sCO_2 turbomachinery concept designs need to be tested and validated as there is a lack of operational experience of sCO_2 power turbine and associated turbomachinery at scale and/or under conditions relevant to commercial operation. Several small closed sCO_2 test loops varying in size (100 kW to 1 MW) have been assembled and the designs and fabrication of sCO_2 turbomachinery have been developed and validated, including the bearings, seals and alternator. The small-scale sCO_2 turbines and compressors developed to date have performed close to the design. A conceptual design of the 10-MWe range high-pressure, high-temperature axial turbo-expander has been developed for application to a sCO_2 based power cycle for CSP conversion under the SunShot Initiatives Program funded by the US DOE. The design and performance of the 10 MWe turbo-expander will be tested in the planned pilot demonstration facility.

Based on its knowledge and experience of steam and gas combustion turbines, Toshiba has developed and constructed a sCO_2 turbine for the NET Power's Allam Cycle demonstration plant. This is a gas-fuelled, 25 MWe (50 MWth) power plant using a semi-closed oxy-combustion transcritical CO_2 power conversion system. The sCO_2 turbine design essentially combines gas turbine and steam turbine technologies, with proven technology adopted whenever possible. It is anticipated that there should not be any major surprises in the turbomachinery design and efficiency as the technology is scaled up.

Practical implementation of a sCO_2 power cycle depends on successful development of a power dense and robust recuperator design compatible with the operating pressures and temperatures of the cycle. Several CHEs (compact heat exchangers) developed for operating in high temperature, high pressure petroleum and chemical processes and some innovative CHE designs are identified as good candidates and are investigated for use in sCO_2 power cycles. R&D is needed to develop designs and construction methods. The printed circuit heat exchanger (PCHE) is the most widely used recuperative type of heat exchanger for sCO_2 power cycle testing.

The proposed indirectly- and directly-heated sCO_2 power cycles have peak operating conditions of 500-700°C/20 MPa and 1200°C/30 MPa, respectively. These operating conditions present challenging requirements for strength and environmental resistance of the construction materials. There are few material choices for long-term commercial power generation applications at >700°C and the leading candidates will be solid solution and precipitation-strengthened Ni-base alloys. It has been suggested that materials selected for advanced ultrasupercritical steam systems would be a good starting point for sCO_2 systems and alloys used in conventional gas turbines could potentially be candidate materials depending on the design. While CO_2 is sometimes described as inert, the effects of CO_2 on high temperature oxidation and internal carburisation have been observed and this is an issue for conventional stainless steels and even for Ni-base alloys at high temperatures. Extensive tests have been conducted worldwide to identify materials compatible with high temperature, high pressure sCO_2 operation. More tests are necessary to understand better the characteristics and behaviour of materials in these conditions.

Several oxyfuel combustors are being developed. Toshiba has built a 5 MWth test rig and successfully tested high pressure oxy-combustion over a wide range of O_2/CO_2 ratios. Toshiba developed a high-pressure combustor for the Allam Cycle demonstration plant, which attained the required pressure of 30 MPa in 2013. The scaled demonstration combustor will be tested using the facilities of the demonstration plant facilities. The demonstration-scale testing will provide real-world experience in putting sCO_2 power cycle and the oxyfuel combustor design into practice. Other oxy-combustors are in earlier stages of development.

A number of computational models have been established for fundamental studies and analysis such as cycle design and performance analysis; analysis of operational performance characteristics of key components; and development and refinement of cycle control strategies. These models provide useful tools for studying and designing sCO_2 power cycles and the individual components.

Developments at system level

A number of attractive sCO_2 power cycle designs have been explored, but it may be that the optimum power cycle has not yet been identified. Several conceptual designs of utility-scale coal-based sCO_2 cycle power plant including designs for key components such as boilers, heat exchangers and compressors have been developed. The viability of these designs needs to be tested and validated.

The first commercial 8 MWe closed sCO_2 Brayton cycle heat engine, developed by Echogen Energy Systems, was brought to the market in 2014. It turns waste heat from various industrial processes to electricity and operates at relatively low temperatures. The ongoing commercialisation of Echogen's heat engines indicates the technical and economic viability of sCO_2 cycles for power generation.

The most notable work in the R&D of directly-heated, semi-closed oxy-combustion sCO_2 cycle is the development of the Allam Cycle. The Allam Cycle is a semi-closed, recuperated, oxy-combustion transcritical CO_2 power cycle, which can reach a high plant efficiency while achieving nearly 100% carbon capture. A 25 MWe natural gas-fuelled Allam Cycle demonstration power plant is being built in Texas (USA) and is scheduled to be commissioned late in 2017.

The coal-based Allam Cycle, fuelled with coal-derived syngas, integrates with a commercially available coal gasifier. Substantial modifications in the combustor design are necessary when changing from natural gas to syngas due to the low heating value of syngas compared to natural gas. There are more technical challenges that need to be tackled in developing the coal version of the Allam Cycle.

Techno-economic analyses by different researchers showed that the Allam Cycle firing syngas could achieve higher net plant efficiency and have a lower levelised cost of electricity than more conventional power cycles with carbon capture. Other studies indicate that syngas-fuelled, semi-closed oxy-combustion sCO_2 cycles could reach a higher net energy efficiency with a higher percentage of carbon capture than an IGCC. However, optimal cycle design and operating conditions are vital for sCO_2 cycles to be competitive.

Significant progress has been made so far in many areas such as developing the design and construction of the key components, identifying the materials suitable for application in sCO_2 power cycles, identifying the optimal sCO_2 cycle configuration for power generation, establishing computer models for fundamental studies and system analyses. Although more needs to be done before a full coal-based sCO_2 cycle power generation system, either indirectly- or directly-heated, can be developed and commercialised with confidence, sCO_2 power systems are starting to emerge in the commercial market. If solutions can be found to resolve all the technical challenges in developing the sCO_2 power cycles, they could offer major opportunities for future power generation from coal in a carbon constrained world.

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