Appendix **D**

Advanced Cycles

A Final Phase IV Report

Prepared by Electric Power Research Institute, June 2014

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Figures and Tables

Advanced Cycles

1. Background

The Electric Power Institute was commissioned to study numerous advanced fossil fuel combustion technologies that have lower GHG emission intensities or could be used to retrofit existing power plants to reduce GHG emissions.

Thermal-electric power plants employing steam-Rankine and combustion turbine power cycles are the predominant method of supplying electric power worldwide and will continue to be for the foreseeable future. At least three factors drive research and development of technologies for use in fossil fueled electric power plants in the 21st century:

1. Higher Efficiency – The drive for higher efficiency in conversion of fuel energy to electricity has been paramount since the very beginnings of producing power from thermal resources and has taken on new importance in recent years as it equates to less fuel use and lower emissions (including CO_2).

2. Reduced Emissions – Protection of public health has been a focus of electric power plant production for a century but has been given greater focus over the last 50 years. This is particularly so in the development of environmental controls to reduce conventional pollutants produced during fossil-fuelled combustion. However, emissions regulations in many regions continue to become more stringent requiring continuing advancement towards near-zero emissions.

3. Reduced CO_2 Emissions – Reducing CO_2 emissions from fossil fueled power plants as a matter of public policy has been discussed widely in public forums for only about a decade. While efficiency improvements can make significant reductions in CO_2 emitted, the deep reductions thought to be necessary will require significant changes to fossil-fired power plants.

These drives are not necessarily mutually supporting. For example: dramatic reductions in CO_2 emissions are likely to constrain improving net plant efficiency.

The drive to improve efficiency and lower emissions has resulted in continuing, but mainly incremental improvements in fossil-fueled power plants over time, while the underlying power production technology has remained essentially unchanged. Efficiency improvements are ultimately bounded by material limits and the underlying thermodynamic properties of the working fluids. Dramatically reducing CO_2 emissions will likely have a major impact on fossil-fueled power plant cost/efficiency based on current state-of-the art technologies for coal-fired and natural gas-fired power. This has driven interest in novel thermal-electric power technologies that can make transformational changes in fossil-fueled power plant design.

A number of the technologies assessed here are "direct-fired", incorporating the fuel combustion products directly into the power production process. These direct-fired technologies are generally applicable to any clean-burning fossil fuel, i.e. fuels that, at a minimum, do not produce solid products of combustion. In general, these technologies may use either natural gas (or other ash-free off-specification gas resources) or coal syngas produced by gasifying coal. In the second decade of the 21st century, the rapid increase in natural gas production from unconventional sources in North America has resulted in natural gas to coal price ratios significantly lower than their historical levels. The resulting availability of low-cost natural gas in North America may facilitate development of the direct-fired technologies with this "clean" fuel before tackling the added challenges of fueling the respective technologies with coal or coal syngas and all of the trace contaminants contained therein.

With the possible exception of the low-temperature organic/NH3-Rankine cycle technology, all of the technologies included here are something other than incremental changes in state-of-the-art power plant technologies identified as the baseline technologies. As such, prior to deploying any of the technologies assessed here, they will need to achieve sufficient technical readiness to warrant the potential risks of making a fundamental change in how power is produced. Achieving the requisite technical readiness to risk the large capital expenditures associated with bulk power plants will require development programs that will cost a significant fraction of the cost of a full scale power plant, but without significant return on the investments prior to the first full scale deployment. This is a public policy challenge that is not addressed in this report, but must be addressed at some time in the future if any of these technologies are to be widely deployed.

2. Report Scope

The final report reviews the current status of a slate of candidate novel power cycles that might be alternatives to the incumbent steam-Rankine cycle and combustion turbine combined cycle power plants used for bulk power applications (>100 MWe). The list of technologies assessed here is not intended to be exhaustive; it consists of technologies for which some level of development has been undertaken as defined by achieving a minimum Technology Readiness level (TRL) based on lab or field trials of at least TRL-5, or have real prospects of doing so shortly. Other candidate technologies can be added to this list as information on their development becomes available.

For each candidate novel technology assessed here, the following are provided in the final report:

- Technology Description – A description of the technology and the range of implementations most commonly anticipated
- Process Operations – Extra-ordinary process operations required for deployment of the candidate technology
- Potential Benefits of Exploiting the Technology – The potential performance of the candidate technology and a general description of the development required to achieve commercial deployment
- Electrical Efficiency Assessment – The reported or calculated electrical efficiency of a power plant employing the candidate technology
- Greenfield Plant Scope of Supply – The system level Scope of Supply required to implement the candidate technology
- Suitability and Scope for Repowering Existing Steam-Electric Power Plants – How the candidate technology might be deployed at existing power plants
- Technical Maturity – Technical readiness of the technology achieved to date based on the respective development efforts and what might be required to advance the technologies to the first commercial installation
- Barriers to Overcome – Technical and/or economic barriers to full scale deployment of the candidate technology
- Reported Cost Estimates – Capital and operating costs estimates for the candidate technology
- Multi-Pollutant Emissions Performance – Reported impact of the technology on emission of criteria pollutants
- Suitability for Partial/Full CO_2 Capture – The impact of the candidate technology on CO_2 emissions. Estimates of CO_2 emission intensity (kg/MWh, net) are included along with the suitability of the technology for biomass-fueling to reduce fossil fuel CO_2 emissions intensity

3. Technologies Overview

3.1. Baseline Technologies

The electrical efficiency and CO_2 emissions intensity performance of the technologies assessed here are summarized in a series of tables below.

Table 1 summarizes the baseline technologies and "retrofit-to-new" variations on these technologies that reduce CO_2 emissions, including atmospheric pressure oxy-pulverized coal combustion with CO_2 capture. The several options evaluated are for a nominal 90 per cent CO_2 capture. Adding CO_2 capture plants to the baseline power plants reduces their efficiency significantly. All of the post-combustion CO_2 capture options could be implemented for partial CO_2 capture with associated increases in net plant efficiency. The oxy-coal with CO_2 capture option cannot be effectively implemented for partial CO_2 capture. Oxy-combustion technologies are suitable only for high (>~90 per cent) CO_2 capture.

Table 1: Performance Summary – Baseline USC Coal and Natural gas Combined Cycle (NGCC) Technologies

Technology	Net Plant Efficiency (HHV)	CO_2 Emissions Intensity (Net Output Basis)	Notes
Coal-fired USC Steam Electric			
Baseline	39.2%	836 kg/MWh	700-800 MW gross generation, PRB coal, 604°C TIT, 90% CO_2 Capture
Retrofit to New PCC	27.2%	111 kg/MWh	
Atmospheric Pressure Oxy-coal	31.5%	106 kg/MWh	
Natural Gas Combined Cycle			
Baseline	51.5&	351 kg/MWh	F-class CT, 566 MW gross generation
Retrofit to New PCC	45.1%	38 kg/MWh	
With PCC and CO_2 Recycle	45.7%	40 kg/MWh	

3.2. High Temperature Power Cycles

Table 2 summarizes the performance of two very high temperature (~700°C) power cycles, the advanced, ultra-supercritical (AUSC) steam cycle and a closed Brayton power cycle using supercritical CO_2 as the working fluid. The net plant efficiency of power plants employing these power cycles is commensurate with the increase in turbine inlet temperature. As they are not gas-side technologies, they do not directly impact CO_2 emissions intensity other than a reduction due to reduced fuel use associated with higher net efficiency.

The most basic version of the Super Critical CO_2 Brayton (SCO_2) cycle being investigated is shown in Figure 1 as the "Simple Cycle". The steps of the cycle include:

Compression – CO_2 near ambient temperature and at a pressure above the critical pressure (1) is compressed to high pressure (2). As the density change is modest, there is only a modest temperature rise due to compression

Recuperative Heat Recovery – The warm, high pressure CO_2 (2) is pre-heated by the hot turbine exhaust (5)

Heat Addition – The pre-heated, high pressure CO_2 (4) is heated to turbine inlet temperature by the heat source

Expansion – The hot, high pressure CO_2 (4) is expanded to a pressure marginally above the critical pressure (5) to produce power

Heat Recovery – The hot, lower pressure CO_2 (5) is pre-cooled by the cool, high pressure CO_2 (2) in the recuperator

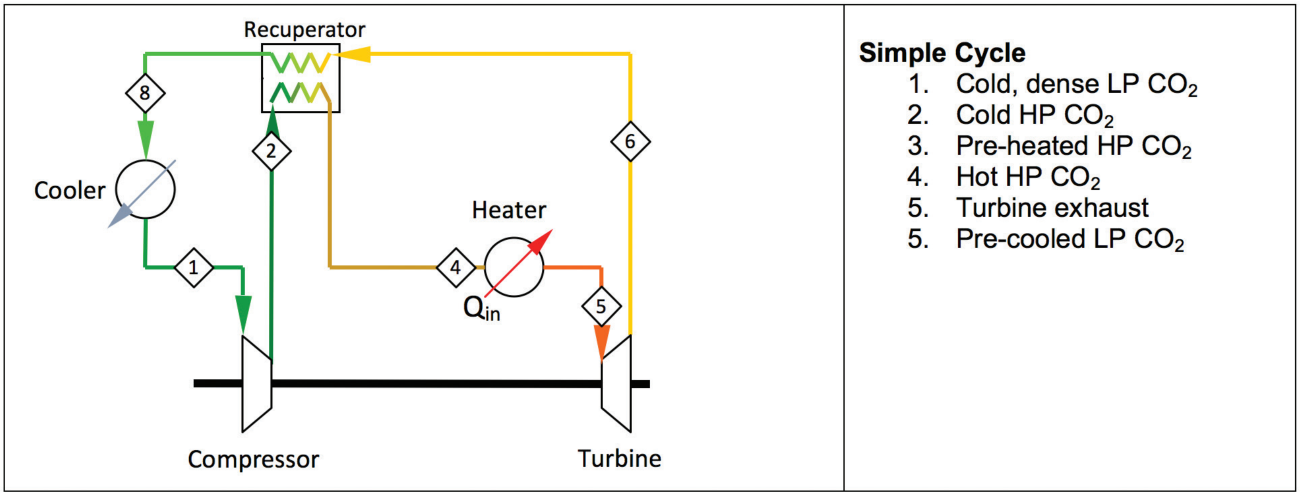
Cooling – The cool, lower pressure CO_2 (6) is further cooled to near ambient temperature by cooling water or ambient air

There are other configurations employing reheat and recompression.

Table 2: Performance Summary – High Temperature Power Cycle Technologies

Technology	Net Plant Efficiency (HHV)	CO_2 Emissions Intensity (Net Output Basis)	Notes
AUSC Baseline, ~700°C TIT	42.7%	768 kg/MWh	700-800 MW gross generation, PRB coal
High Temperature Closed Brayton Power Cycle, 700°C TIT	Up to 45%	As low as 730 kg/MWh	Dependent on thermal integration with a fired CO_2 heater, designs yet to be prepared.

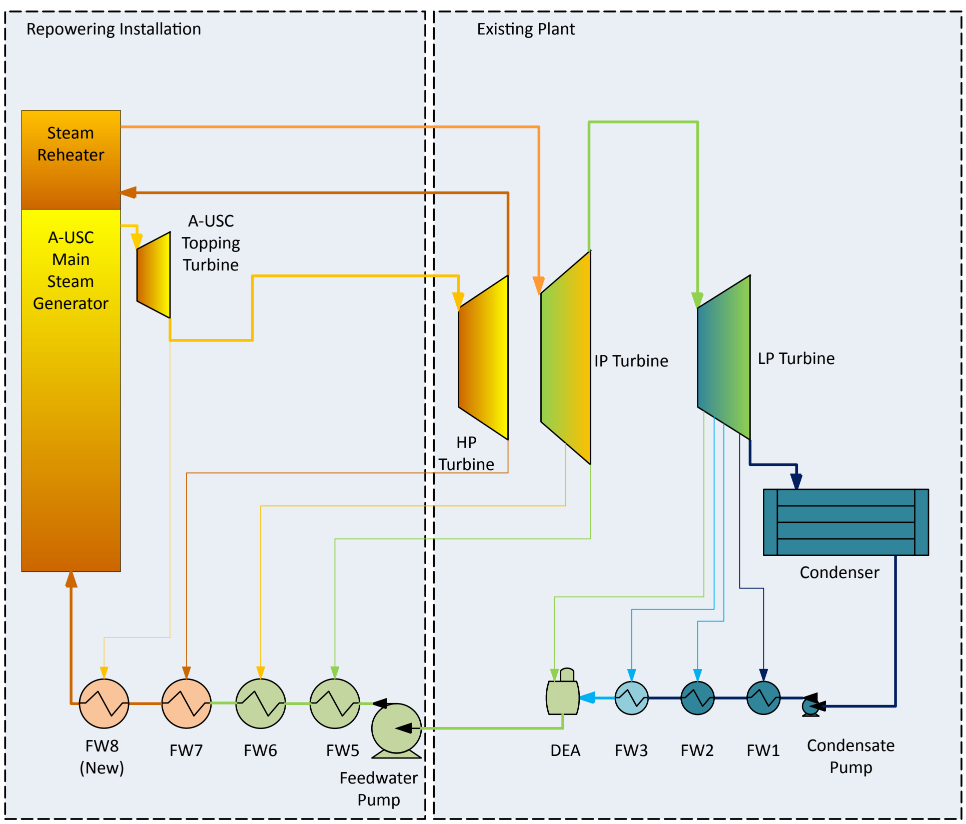
Figure 1: Common Closed Brayton Cycle Proposed for Power Generation using Supercritical CO_2 *as the Working Fluid*



3.3. High Temperature Topping Cycles

Table 3 summarizes the performance of three high temperature topping cycles. Adding an AUSC steam topping cycle, as shown in Figure 2 increases the capacity of a sub-critical bottoming cycle by approximately 22 per cent with a corresponding increase in net plant efficiency of 8-9 percentage points. The same is generally true for adding a closed Brayton topping cycle as shown in figure 3. As neither of these are gas-side technologies, they do not directly impact CO_2 emissions intensity other than a reduction due to reduced fuel use associated with higher net efficiency.

Figure 2: Schematic Diagram of Repowering an Existing Sub-critical Steam Plant with an A-USC Topping Turbine



In this configuration, as shown in Figure 3, an additional Closed Brayton cycle provides heat to existing steam turbines. Heat in the super-critical CO_2 working fluid exiting the IP turbine provides heat to produce steam supplied to existing turbines are points nine and 11 below. Natural gas is used to provide the heat required before points one and three below.

Figure 3: Repowered Closed Brayton Topping Cycle (with reheat)

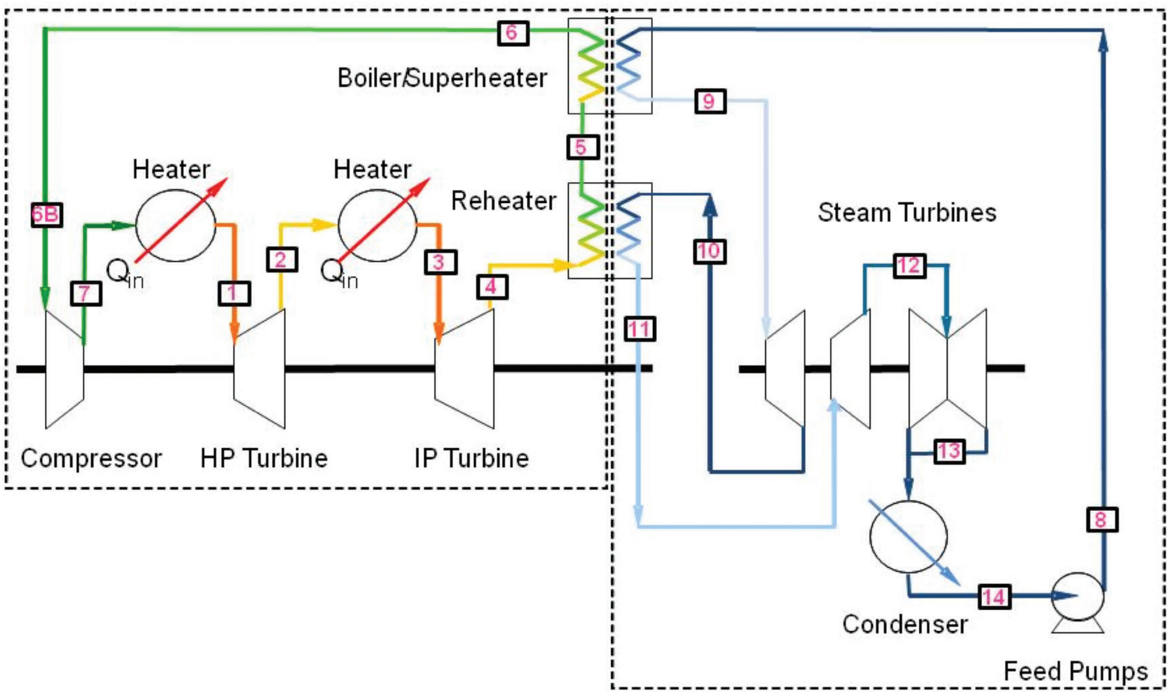
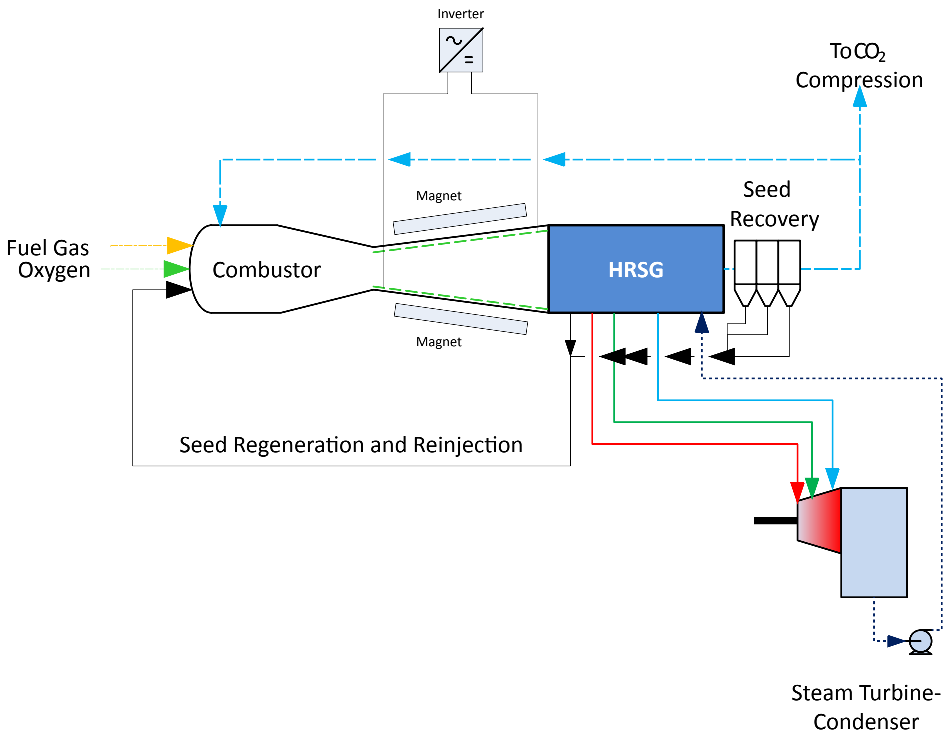


Figure 4 shows a magneto-hydrodynamic (MHD) topping cycle. Direct current (DC) power is produced by an MHD generator when:

- The high temperature gas plasma containing positive ions and free electrons is accelerated through the MHD flow channel. Plasma is produced by high temperature oxy-combustion of fuel
- The positive ions and electrons are forced in opposite directions to collector electrodes by the magnetic field imposed on the flow channel
- The electrons from the anode flow through an external circuit to combine with the positive ions at the cathode

There are reasonable prospects that an oxy-natural gas MHD plant with CO_2 capture will perform better than an NGCC plant with CO_2 capture. The MHD technology, however, will require significant development to achieve this better performance.

Figure 4: Flow Schematic of Oxy-Natural Gas Open Cycle MHD Power Generation Combined Cycle Plant (Magnetic Field direction up/down; charge collection electrodes side to side)



All of these topping cycle technologies could be used to repower existing plants. The AUSC and closed Brayton cycle technologies are not gas-side technologies and do not directly impact CO_2 emissions intensity other than a reduction due to reduced fuel use associated with higher net efficiency. The oxy-natural gas MHD technology is, like other oxy-combustion technologies, suitable for plants that require high levels of CO_2 capture.

Table 3: Performance Summary – High Temperature Topping Cycle Technologies

Technology	Net Plant Efficiency (HHV)	CO_2 Emissions Intensity (Net Output Basis)	Notes
AUSC Topping Cycle	40.7%	10% reduction	~22% increase in net plant capacity. Dependent on existing steam cycle efficiency
Closed Brayton Topping Cycle	42.4%	17% reduction	~24% increase in net plant capacity. Dependent on existing steam cycle efficiency
MHD Topping Cycle (Oxy-natural Gas)	41%-53%	<40 kg/MWh	Steam-electric bottoming cycle

3.4. Bottoming Cycles

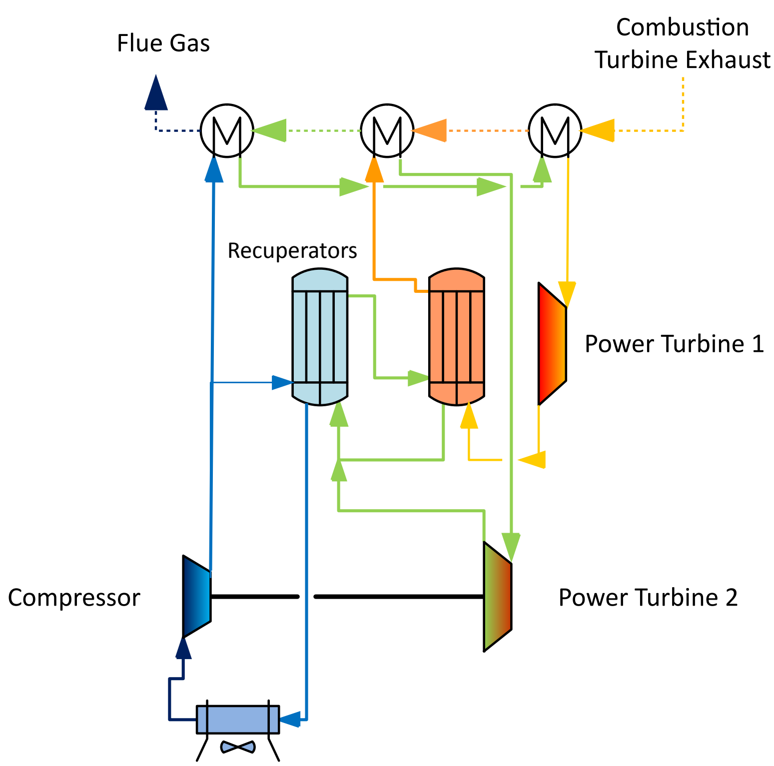
Table 4 summarizes the performance of two bottoming cycle technologies. The closed Brayton bottoming cycle is an alternative to the standard steam-Rankine bottoming cycles used for combustion turbine combined cycles. The closed Brayton bottoming cycle as shown in Figure 5, may be an attractive option for adding to small 30 to 50 MW simple cycle gas turbines since they may be less expensive than comparable steam-Rankine bottoming cycles at this size.

While commonly used to convert lower temperature heat resources to power, the ammonia/organic Rankine bottoming cycle application assessed here is as a replacement for (and amendment to) the last few low pressure stages of a steam turbine. The most likely application for this technology is for those plants that require dry cooling. In these applications, there may be a capital cost benefit for the bottoming cycle technology. The technology may also be suitable for exploiting very low condensing temperatures as are found in high latitudes. Various configurations employing heat from flue gas, condensing steam and other sources of low grade steam have been studied.

Table 4: Performance Summary – Bottoming Cycle Technologies

Technology	Net Plant Efficiency (HHV)	CO_2 Emissions Intensity (Net Output Basis)	Notes
Closed Brayton Bottoming Cycle (NG-fueled Aero-derivative CT)	50%	33% reduction	
Ammonia/Organic Rankine Bottoming Cycle	Up to 5 percentage point increase at 4°C condensing temperature	Reduction commensurate with efficiency increase	Benefits are maximized for air-cooled condensers

Figure 5: Generic "Cascaded" Closed Brayton Cycle Configuration for a Bottoming Cycle Application

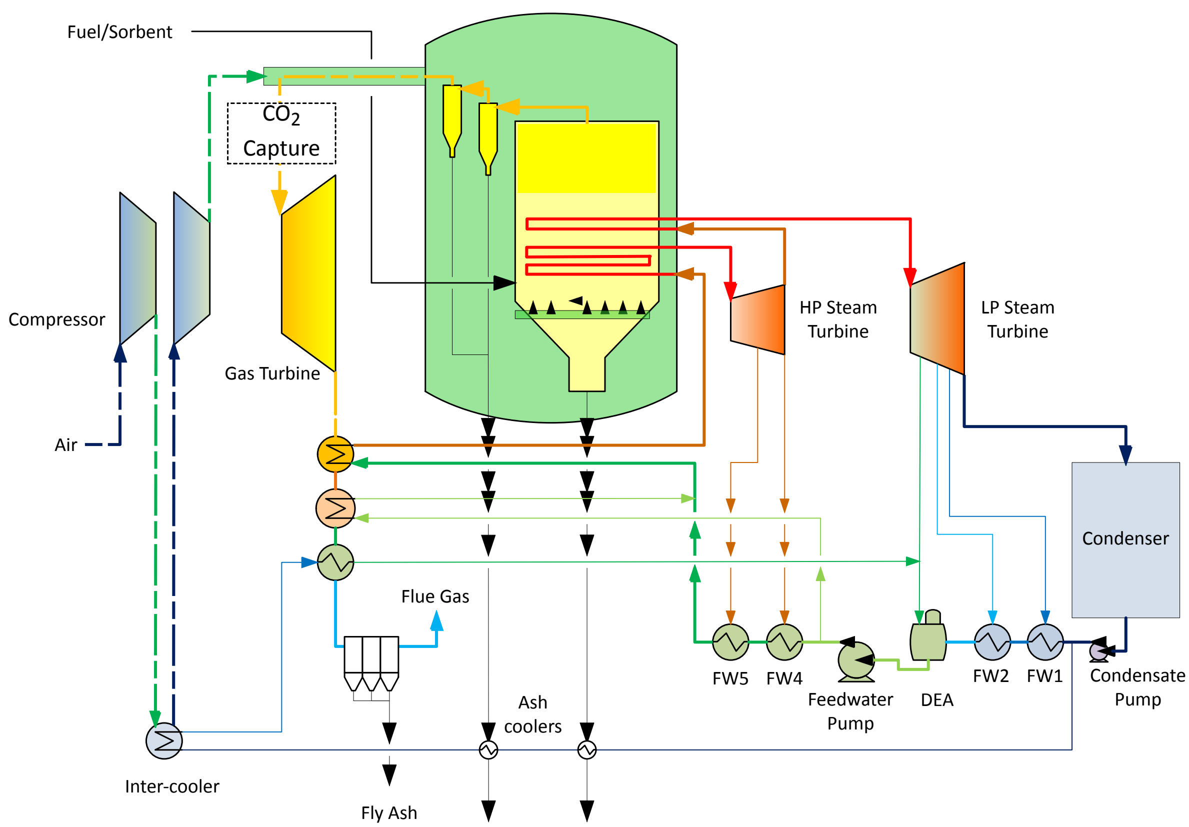


3.5. Direct Fired Cycles

If a fluidized-combustor is operated at pressure, as shown in Figure 6, the flue gas can be expanded through a gas turbine to generate electricity in addition to that generated by the steam turbine. This combined cycle arrangement raises generating efficiency approximately four percentage points higher than the steam cycle alone. The only pressurized fluidized-bed combustors (PFBC) plants that have entered commercial service are bubbling beds.

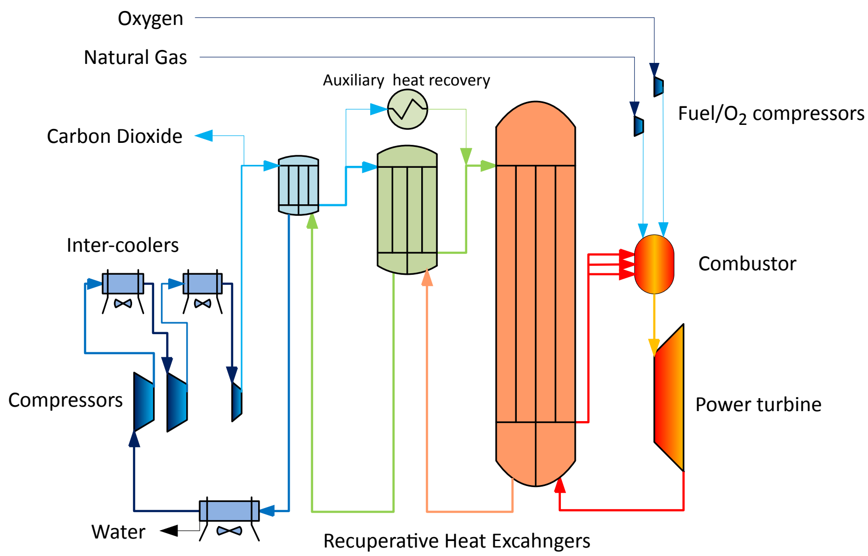
The 850°C (1560°F) flue gas leaving the PFBC cyclones is cooled going into the CO_2 capture process and reheated coming out of the CO_2 capture process in a tubular recuperator. The CO_2 capture technology proposed by Sargas is based on the Benfield process which uses a potassium carbonate/bicarbonate chemistry. The absorption and desorption are conducted at approximately the same temperature, near 100°C (212°F). Absorption is conducted at flue gas pressure (~12 bar). Desorption is conducted at a lower pressure. Thermal use is between 680 and 910 Btu/lb CO_2 (1,580-2,120 kJ/kg CO_2). The cooled flue gas passes through the capture plant and the CO_2-depleted flue gas flow passes back through the recuperator to be reheated to 815°C (1500°F) before being expanded through the turbine.

Figure 6: Simplified Schematic of Bubbling PFBC Power Plant



The CO_2-cooled technology being pursued by NET Power, as shown in Figure 7 below, is a direct-fired version of the closed Brayton cycle technology. It may have an efficiency with CO_2 capture as high as the baseline NGCC technology without CO_2 capture; a notable feat, if it can be achieved.

Figure 7: Simplified NET Power Direct-Fired Oxy-Natural Gas Process Schematic



In the Clean Energy System (CES) process shown in Figure 8, fuel is combusted with pure oxygen in the presence of steam. This produces a high purity stream of CO_2 flue gas, which can be dried and compressed.

Figure 8: Simplified Flow Diagram for Clean Energy Systems (CES) Oxy-natural Gas with CO_2 Capture Power Plant Concept

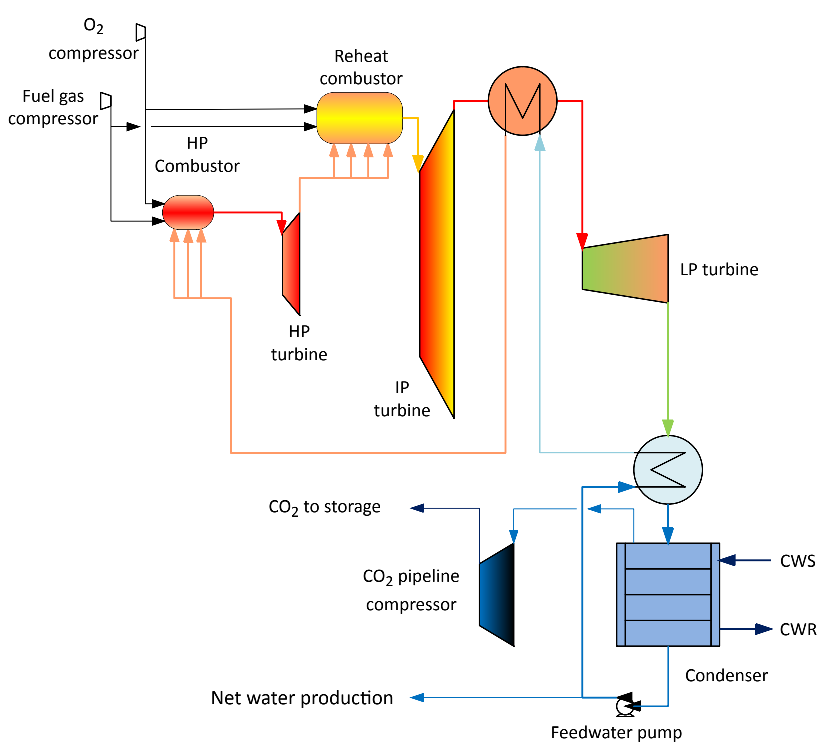


Table 5 summarizes the performance of one direct, coal-fired technology and two direct-fired oxy-natural gas combustion turbine technologies. The turbo-charged boiler technology is being advanced for coal-fired power with CO_2 capture. The data in Table 5 should be compared to the corresponding coal-fired CO_2 capture cases in Table 1. It appears that the turbocharged boiler (Bubbling PFBC) technology might have higher net plant efficiency at high CO_2 capture than the "retrofit-to-new" baseline technologies. Both of the oxy-natural gas combustion turbine technologies (CES, NET Power) are expected to have negligible CO_2 emissions. The water-cooled technology being pursued by CES looks to be approximately as efficiency as NGCC with CO_2 capture.

Table 5: Performance Summary – Direct-fired Power Cycle Technologies

Technology	Net Plant Efficiency (HHV)	CO_2 Emissions Intensity (Net Output Basis)	Notes
Turbo-charged, Coal-fired Boiler with Benfield CO_2 Capture	36.3%	94 kg/MWh	
CO_2-cooled Oxy-natural Gas CT	53.1%	nil	NET Power
Water-cooled Oxy-natural Gas CT	35%-45%	nil	Depends on final configuration. Clean Energy Systems

3.6. Pressurized Oxy-fuel and Chemical Looping Combustion

Table 6 summarizes the performance of two classes of advanced oxy-coal with CO_2 capture technologies. These performance results should be compared with the "retrofit-to-new" PCC and atmospheric pressure oxy-coal results in Table 1. Both of these technologies have the potential for higher efficiency than either of the baseline technologies with CO_2 capture. As with all oxy-combustion technologies for CO_2 capture, these options cannot be effectively implemented for partial CO_2 capture and are suitable only for high levels of CO_2 capture.

Figure 9 shows a schematic for an oxy-fueled pressurized fluidized bed combustion process. Coal is combusted at high pressure with oxygen. Steam is created by the heat in the fluidized bed and is used to drive steam turbines.

Figure 9: Simplified Gas-side Block Flow Diagram for Aerojet Rocketdyne Pressurized Oxy-Coal Combustion Power Process

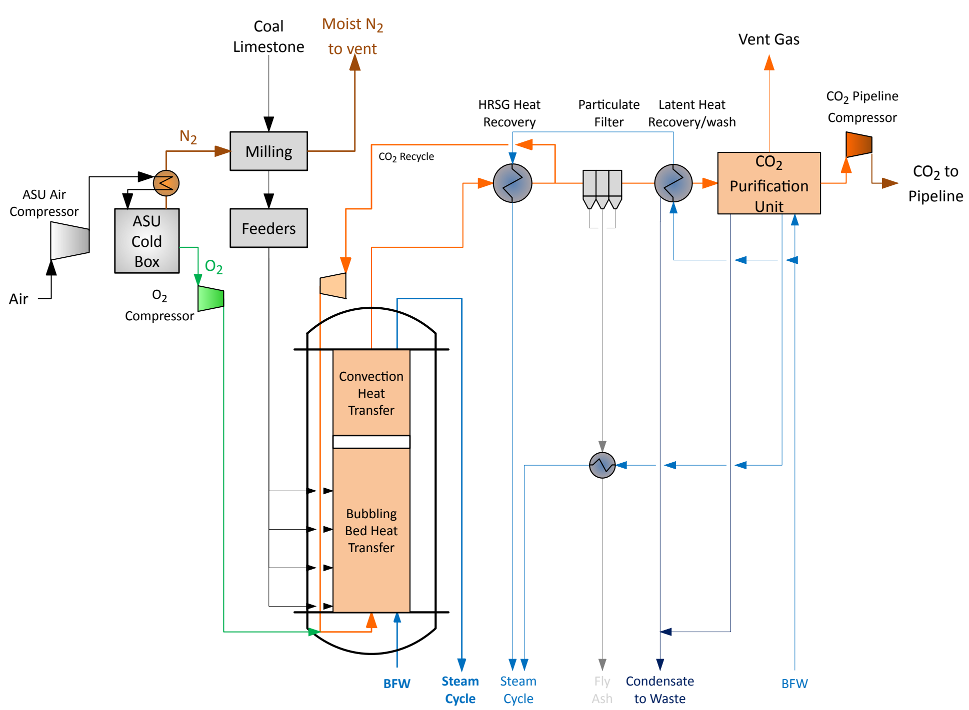


Figure 10 shows a schematic of a chemical looping combustion process. An oxygen carrier in the fuel reactors liberates oxygen to combust the fuel. A hot flue gas consisting of mainly CO_2 and water is produced. The gas is used to produce steam that is then used to drive steam turbines. Once it is cooled, the flue gas is dried to remove water and compressed for delivery to a pipeline. The spent oxygen carrier is set to the air reactor where it is exposed to air. Oxygen is added to the carrier and it is returned to the fuel reactor.

Figure 10: Generic Conceptual Process Schematic for Chemical Looping Combustion with CO_2 Capture

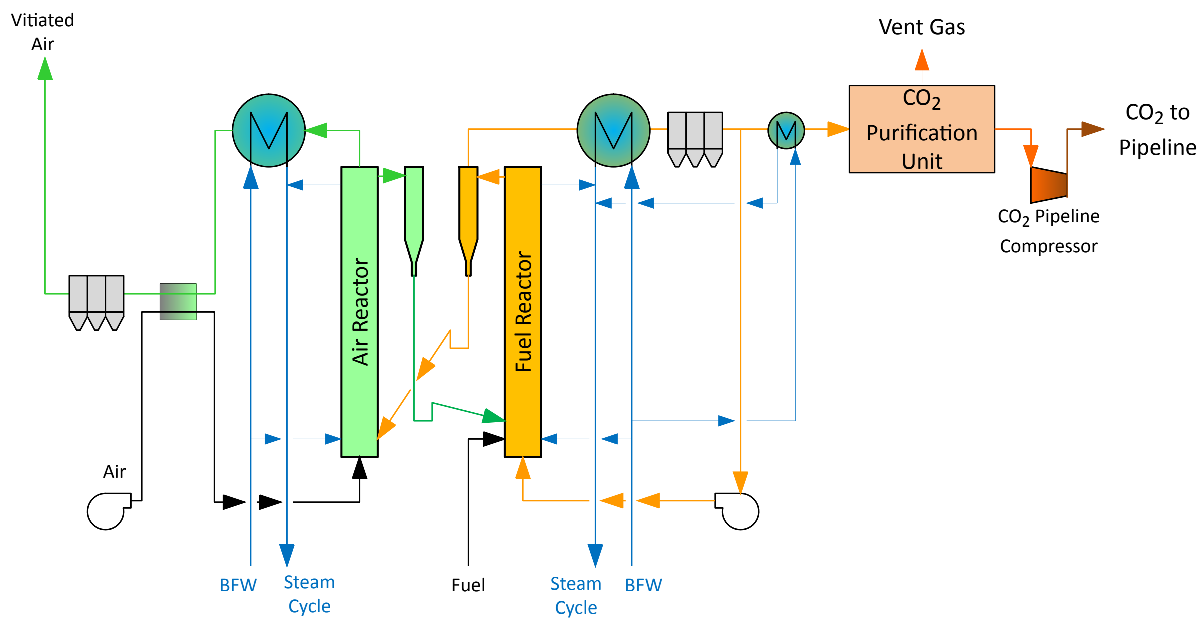


Table 6: Performance Summary – Advanced Oxy-Combustion with CO_2 Capture Technologies

Technology	Net Plant Efficiency (HHV)	CO_2 Emissions Intensity (Net Output Basis)	Notes
Pressurized Oxy-coal Combustion	33%-37%	17-95 kg/MWh	Aerojet-Rocketdyne and WUSTL Technology
Chemical Looping Combustion	35.2%	27 kg/MWh	B&W / OSU Technology

4. Recommendations

4.1. Repowering Candidates

Repowering and life extension of existing power plants are very similar options. Decisions to undertake either strategy rather than build new capacity depend on a wide variety of factors including condition of existing equipment, electrical market conditions, permitting (or re-permitting) costs, etc. A number of the technologies assessed here will be technically suitable for repowering. Whether they are economically suitable for repowering must be made on a case by case basis.

The technologies suitable for repowering are listed below along with recommendations for CCPC involvement in development of the respective technologies.

- Advanced, Ultra-Supercritical (AUSC) Steam Topping Cycle – Materials meeting the ASME boiler and pressure vessel code and the ASME piping code have been developed. These materials have not yet been shown to be durable in coal-fired boiler service. This is the major challenge to serious consideration of repowering an existing sub-critical steam-electric plant with an AUSC topping turbine. While achieving lower CO_2 emissions associated with the higher efficiency AUSC steam power cycle, by itself, this repowering option will not result in a coal-fired power plant achieving CO_2 emissions of 420 kg/MWh (net). A gas-side technology change would be required to meet this emissions standard.

Recommendation: Maintain a watching brief on worldwide activities that seek to assess durability of AUSC materials in coal-fired service.

- Closed Brayton Topping Cycle – In addition to the scope identified for AUSC Topping cycle indicated above, closed Brayton cycle technology will also need to be developed in order to adopt this repowering option.

  Recommendation: In addition to maintaining a watching brief on high temperature heat transfer materials, a watching brief should be maintained on development of closed Brayton cycle technology. Participation in one or more pilot deployments of this technology might also be considered.

- MHD Topping Cycle – A considerable amount of research and development will be required to bring MHD technology to sufficient technical readiness for a field deployment. On the other hand, early deployments of this technology are likely to be repowering projects.

  Recommendation: Maintain a watching brief on development of MDH technology, and look for opportunities to nominate suitable power plants for scoping studies.

- Closed Brayton Bottoming Cycle – This technology is probably suitable only for repowering aero-derivative combustion turbines and is not a suitable technology for repowering coal-fired steam-electric plants.

  Recommendation: No recommendation.

- Organic/Rankine Bottoming Cycle – The economic feasibility of deploying this technology has not been rigorously assessed. In addition to the efficiency/capacity benefit at low ambient temperatures, there may be a significant capital/maintenance benefit if air-cooling is required. Nonetheless, consideration of this technology for repowering will entail significant assessment of the existing steam turbine and condenser. It is likely that deploying this technology in a repowering application will be necessary before it can be seriously considered for net-build.

  Recommendation: One or more site-specific studies should be undertaken to detail the costs of repowering with a bottoming cycle. This study should include capital, fuel operating and non-fuel operating benefits with projections for the new-build case.

- Turbocharged Boiler with CO_2 Capture – The base turbocharged boiler technology has achieved technical maturity but has not achieved widespread commercial acceptance. The addition of partial pressurized post-combustion CO_2 capture to the f low sheet results in an overall package that might be suitable for repowering to achieve CO_2 emissions of 420 kg/MWh (net). (The scope may also include installing a topping turbine to increase capacity/efficiency).

  Recommendation: The next step for evaluating this technology is to conduct a site-specific engineering and economic evaluation to scope the repowering effort and develop capital costs as well as overall operating benefits.

- Pressurized Oxy-coal and Chemical Looping Combustion – The scope of a repowering project will be nearly the same for these technologies; the existing boiler is demolished along with much of the air quality control system. A new steam generator is installed to supply the existing steam turbine. (The scope may also include installing a topping turbine to increase capacity/efficiency.) Both of these technologies are best suited for high CO_2 capture; the partial capture benefits are modest to achieved 420 kg/MWh (net), rather than <100 kg/MWh (net) for which the technologies are well-suited. On the other hand, if there is an enhanced oil recovery (EOR) market for the captured CO_2, these technologies may be very suitable for repowering.

  Recommendation: Maintain a watching brief on the several development efforts for this technology. Any systematic evaluation of repowering options should include these options, particularly if an EOR market for the captured CO_2 is anticipated.

4.2. Greenfield Candidates

The primary constraint to deployment of new coal-fired power plants in Canada will be achieving CO_2 emissions under 420 kg/MWh (net). It will not be possible to achieve these emissions levels by improving power cycle efficiency; active measures on the combustion side will be required.

The technologies suitable for greenfield coal-fired power plants are listed below, along with recommendations for the CCPC to be involved in development of the respective technologies.

- Advanced, Ultra-supercritical (AUSC) Steam-electric Plants – Materials meeting the ASME boiler and pressure vessel code and the ASME piping code have been developed. These materials have not yet been shown to be durable in coal-fired boiler service. This is the major challenge to serious consideration of repowering an existing sub-critical steam-electric plant with an AUSC topping turbine. While achieving lower CO_2 emissions associated with the higher efficiency AUSC steam power cycle, by itself, an AUSC power plant will not result in a coal-fired power plant achieving CO_2 emissions of 420 kg/MWh (net) without a gas-side technology change.

  Recommendation: Maintain a watching brief on worldwide activities that seek to assess durability of AUSC materials in coal-fired service.

- Closed Brayton Power Cycle Plants – In addition to the scope identified for AUSC Steam-electric power plants indicated above, closed Brayton cycle technology will also need to be developed in order to adopt this repowering option.

  Recommendation: In addition to maintaining a watching brief on high temperature heat transfer materials, a watching brief should be maintained on development of closed Brayton cycle technology. Participation in one or more pilot deployments of this technology might also be considered.

- Closed Brayton Bottoming Cycle – This technology is suitable for increasing the capacity of an aeroderivative combustion turbine-generator. It will compete with the steam bottoming cycles commonly supplied with these combustion turbines.

  Recommendation: If and when an aeroderivative combustion turbine acquisition is contemplated, an engineering and economic evaluation of deploying this technology should be conducted to assess costs and benefits in comparison with the options of installing no bottoming cycle and installing the steam bottoming cycles commonly supplied. Participation in one or more field deployments of prototype closed Brayton bottoming cycle power plants should be considered.

- Organic/NH_3 Bottoming Cycle – The economic feasibility of deploying this technology has not been rigorously assessed. In addition to the efficiency/capacity benefit at low ambient temperatures, there may be a significant capital/maintenance benefit if air-cooling is required. It is likely that deploying this technology in a repowering application will be necessary before it can be seriously considered for new-build.

  Recommendation: The next step for advancing this technology is to conduct an engineering and economic evaluation of deploying the technology in a new plant. This study should include capital, fuel operating and non-fuel operating benefits with projections for the new-build case.

- Pressurized Oxy-coal and Chemical Looping Combustion – Both of these technologies are best suited for high CO_2 capture; the partial capture benefits are modest to achieved 420 kg/MWh (net), rather than <100 kg/MWh (net) for which the technologies are well-suited. On the other hand, if there is an EOR market for the captured CO_2, these technologies may be very suitable for repowering. It is likely that pressurized oxy-coal technology can be deployed sooner that can chemical looping combustion technology for a greenfield application. Early deployment should, at a minimum, include a high-efficiency ultra-supercritical steam power cycle.

  Recommendation: Maintain a watching brief on the several development efforts for this technology. Any systematic evaluation of new-build options should include these options, particularly if an EOR market for the captured CO_2 is anticipated.

- Turbo-charged Boiler with CO_2 Capture – The base turbocharged boiler technology has achieved technical maturity but has not achieved widespread commercial acceptance. The addition of partial pressurized post-combustion CO_2 capture to the flow sheet results in an overall package that might be suitable for greenfield power plants to achieve CO_2 emissions of 420 kg/MWh (net). The scope should also include, at a minimum, a high-efficiency ultra-supercritical steam cycle.

  Recommendation: The next step for evaluating this technology is to conduct an engineering and economic evaluation to scope the plant and develop capital costs as well as overall operating benefits. If the results of this study are favorable, pilot plant trials of candidate coals would likely be the follow-up step.