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GHGT-12

Maintaining the power output of an existing coal plant with the addition of CO₂ capture: Retrofits options with gas turbine combined cycle plants

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Abstract

It is likely that a significant number of existing pulverised coal-fired power plants will be retrofitted with post-combustion capture as part of a global rollout of carbon capture and storage. Previous studies have demonstrated that the energy penalty for post-combustion carbon dioxide (CO₂) capture can be greatly minimised by effective integration of the capture system with the power cycle. Nevertheless, the power output of the site is, in most cases, reduced and the volume of electricity sales would drop. For other plants, the existing steam cycle may not be able to be integrated effectively for steam extraction, or space and access around/to the steam cycle may be impossible. As an alternative to steam extraction, it is possible to retrofit existing coal plants with a gas turbine combined cycle plant (CCGT) to maintain, or even increase, the site power output. The gas turbine can be integrated to the existing coal plant in various ways to supply all the heat, or a fraction of the heat, and the power required for the capture systems. An important consideration is whether carbon emissions from both, the combined cycle and the retrofitted coal plant are captured, or from the latter only.

This paper examines these different options for carbon capture retrofits to existing coal plant and presents a novel configuration with the sequential combustion of gas turbine flue gas in the existing coal boiler while capturing carbon emissions from the combustion of coal and natural gas.

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Retrofit, post-combustion capture, coal plant, gas turbine combined cycle

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1. Introduction

One important contribution to achieving ambitious CO₂ emission reduction levels is expected to be equipping, new build fossil-fuel power plants with carbon capture and storage (CCS). An important fraction of the fleet of existing fossil-fuel power plants can also be expected to be retrofitted with CCS in the next decades and play an important role in mitigating CO₂ emissions from power generation [1]. It is likely that a significant number of pulverised coal-fired (PC) power plants will be retrofitted with post-combustion capture as part of a global rollout of CCS.

Previous studies [2] have demonstrated that carbon capture can be a cost-effective retrofit option if effective integration of the capture system with the power cycle can be achieved. Integrated retrofit strategies with steam extracted from the power cycle to provide thermal energy for solvent regeneration result, however, in a reduction of net plant output and of revenues from electricity sales. But for many existing sites, access to the power cycle and/or to appropriate steam extraction pressure may not be possible and unnecessary thermodynamic losses would have to be incurred.

If there is no access to the power cycle, the simplest way to supply the steam and electrical power required by the carbon capture and CO₂ compression is to use an additional fuel source. Since the marginal efficiency of natural gas ancillary boilers for heat matched retrofit is significantly lower than other options available, i.e. of the order of 12% LHV, this option has been disregarded in this study [3]. Instead, the work focuses on option where an acceptable fraction of the calorific value of the natural gas is recovered through the generation of power and heat.

For example, the addition of gas turbine (GT) with a single pressure Heat Recovery Steam Generator (HRSG) supplying heat to the carbon capture plant has been examined in various engineering studies of CCS projects in recent years [4].

In these projects, no consideration was, however, given to carbon emissions from the combustion of natural gas. These emissions cannot indefinitely be expected to be acceptable in order to largely decarbonize power generation, as is currently suggested by the UK Committee on Climate Change [10]. As an alternative, it is possible to add a separate carbon capture unit to the CCGT or, if efficient mixing of large gas volumes can be achieved, to treat the flue gas from the coal and the gas plant in the same carbon capture unit. Since the latter may prove to be challenging with stratification in large duct work, one way to achieve carbon capture from both fuel sources in a single carbon capture unit, and at the same time reduce the total volume of flue gas to be treated, is to feed the gas turbine flue gas to the boiler. This is achieved by replacing a portion of the air from the original fans. Another advantage is the possibility to integrate the HRSG to complement boiler feedwater heating in the existing steam cycle and effectively operate the existing steam turbines as the combined cycle of the CCGT.

This paper examines a range of different options of carbon capture retrofit to existing coal plants and the factors that may be important in determining overall retrofit project performance. It evaluates key performance indicators for a range of retrofit scenarios taking into account the specificity of the existing site and the regulatory frame work where the plant may operate. Particular attention is given to the following aspects:

- Space around and access to the existing power cycle for steam extraction
- Possibility of a fully integrated retrofit, e.g. if the plant is built as carbon capture-ready
- Steam cycle parameters for efficient integrated retrofit
- Transmission capacity of the existing site
- Retrofit options to increase the output of the site
- Retrofit options to maintain the output of the site
- Integration between the existing coal plant and the gas turbine cycle with a fraction, possibly all, of the thermal energy for solvent regeneration supplied by the gas CHP plant.
- Capture of the emissions from the combustion of natural gas.
- Capture level and carbon intensity of electricity generation to match an emission performance standard of 450 gm/kWh, circa 1000 lb/MWh, to meet as standard equivalent to emissions from an unabated CCGT plant.
- Marginal thermal efficiency of the additional usage of natural gas
- Electricity output penalty, as the amount of electricity necessary to capture and compress unit of CO₂ on a mass basis.

Nomenclature

CCS	Carbon capture and storage
CO ₂	Carbon dioxide
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
DCC	Direct contact cooler
EOP	Electricity output penalty
GT	Gas turbine
HRSG	Heat recovery steam generator
HP	High pressure
IP	Intermediate pressure
LP	Low pressure
NO _x	Nitrogen oxides
PM	Particulate matter
C ₃ H ₈	Propane
PC	Pulverised coal-fired
SO ₂	Sulfur dioxide

2. Design Basis

The design basis of the existing coal plant is identical for each configuration. The modelling methodology is consistent for each configuration. Models of the boiler, the steam cycle and the ancillaries of a pulverised coal plant and of a series of CCGT configurations have been developed in Mathcad and validated by the process simulator Aspen Plus V8.

2.1. Boiler

Boiler performance specifications are based on a DOE report establishing a common baseline for the comparison of fossil fuel plants configurations [5]. They are selected based on a survey of boiler and steam turbine original equipment manufacturers for commercial projects in the US with subcritical units [6].

The steam generator of the PC Power Plant is a natural circulation balanced draft unit with two parallel paths for gases and subcritical parameters. The steam generator consists of a water wall furnace, a platen secondary superheater and a final superheater in the upper region of the furnace and a primary superheater, reheater, and economizer in the parallel pass convection section. There are also control dampers at the end of the parallel pass to regulate the reheated steam temperature. Secondary Air is driven by a forced draft fan to a regenerative air preheater and then routed to the windbox where it is distributed to the burners. The Primary Air Fan provides air to a separation section of the regenerative air preheater. A portion of the air is passed unheated around the air preheater to temper the primary air and reach the desired pulverized fuel-air mixture outlet temperature. The fuel is ground up and then dried and transported by a flow of primary air to coal classifier sections where fuel particles are carried by the primary air through the coal-air conduits to the burners.

For retrofit options where gas turbine flue gas is introduced to the boiler to replace a fraction of the combustion air, the first stage of boiler performance calculations sizes the geometry of the heat transfer equipment and defines the required operating conditions with air-firing. Combustion calculations, mass and energy balances and heat transfer coefficient are then determined. The Peng-Robinson equation of state with Boston-Mathias modifications (PR-BM) have been selected as the property method for the flue gas and the National Bureau of Standards Steam Tables (SteamSTB) for the steam.

The surface area of the different heat exchangers is then selected to reach the boiler performance specifications of the design basis with air firing and then evaluate the behavior of the boiler with different gas compositions and flow rates when it is retrofitted by replacing part of combustion air by gas from the CCGT. In order to calculate the heat transfer in the boiler furnace we followed the semiempirical method suggested by I. E. Dubovsky [7].

2.2. Steam turbine and gas turbine modelling

Stodola's ellipse law is used to predict the extraction pressures for the retrofitted steam turbines configuration when turbine nozzles are not choked [8]. The stage swallowing capacity, k , for each steam turbine has been determined at original conditions and it will be used to predict steam turbines behaviour when they are retrofitted for carbon capture.

For retrofit options with a CCGT, the gas turbine is followed by an unfired three pressures level HRSG with High Pressure (HP) and Intermediate Pressure (IP) steam turbines.

The pressure ratio of the gas turbine of the CCGT is modified for each retrofit case in order to reach a common exhaust gas temperature of 623 C for all cases.

The natural gas flow rate is calculated for each configuration in order to either maintain the power output of the site or to supply the amount of thermal heat required by the capture plant.

2.3. Post-combustion capture plant

The post-combustion capture process using an amine-based solvent is located downstream of the conventional pollutant controls for particulate matter (PM), nitrogen oxides (NO_x) and sulfur dioxide (SO₂). The flue gas is conditioned in a direct contact cooler (DCC) prior to contact with the amine solution. Models of the Carbon Capture Plant and the CO₂ compression system use the process simulator Aspen Plus V8. The amines property package of Aspen Plus is used to model the electrolyte thermodynamic system and the Soave-Redlich-Kwong (SRK) and the Peng Robinson equations of state (PR) have been selected as the property method for the CO₂ and C₃H₈ respectively. RadFrac columns are selected for both the absorber and the stripper.

The carbon capture plant is sized for the resulting compressed CO₂ flow of each power plant configuration. A setup with two absorber trains with a 12.9m diameter and 17m of column height (not including the water wash) is used throughout of the study.

CO₂ from the stripper overheads is compressed to 13 bar in a three-stage centrifugal compressor. The inter-coolers are designed to cool the CO₂ down to 50C by means of condensate water heating. The number of compression stages depends on the temperature limit and the compression ratio. It has been assumed a 120C temperature limit and a compression ratio of 2.3. The CO₂ is then liquefied by the use of a propane refrigeration system and pumped to a pressure of 140bar [9].

3. Comparison of retrofit options

The various options considered in this work have been put into different groups to make easier the comparison of the results.

3.1. Fully integrated retrofit with access to the power cycle

All the heat and power required for the capture process is supplied from the existing coal plant.

The thermal energy of solvent regeneration is provided by steam extraction from the steam turbines and the electrical power required for the capture process is supplied by the existing power cycle. Consequently, the electricity output from a retro-fitted site with post-combustion carbon capture is reduced. In order to find the optimum lean loading that minimises the power output drop of the site a sensitivity analysis was carried out and the results are shown in Figure 1. It is important to highlight that this option will lead to an underutilised grid connection capacity and a loss in revenue from electricity sales.

The most relevant parameters are shown in Table 1.

Table 1.- Performance results of the fully integrated retrofit and heat matched retrofits.

		HEAT MATCHED RETROFIT					
		PC Power Plant	Integrated Retrofit	Unabated GT+HRSG	Gas Standard GT+HRSG	Unabated CCGT	Gas Standard CCGT
<i>Retrofitted PC Power Plant</i>							
Coal thermal input	MWth	1517,93	1517,93	1517,93	1517,93	1517,93	1517,93
Gas thermal input	MWth	0,00	0,00	1011,81	538,62	1293,10	594,40
Power output	MWe	600,30	479,33	895,53	750,20	1139,05	839,56
Carbon intensity of electricity generation	g CO ₂ / kWh	765,29	96,02	257,49	450,01	247,50	450,02
Overall efficiency	%	39,55	31,58	35,40	36,48	40,52	39,75
<i>Carbon Capture Plant</i>							
Lean loading		-	0,25	0,25	0,25	0,25	0,25
Carbon capture rate		-	90,00	90,00	90,00	90,00	90,00
Overall carbon capture rate		-	90,00	64,20	39,47	59,46	33,47
Total gas flow rate	kg/s	632,76	632,76	1451,78	1068,76	1679,47	1113,90
Gas flow rate to CC Plant	kg/s	-	632,76	632,76	336,84	632,76	290,86
CO ₂ fraction in gas to CC Plant	vol %	-	0,14	0,14	0,14	0,14	0,14
Reboiler thermal heat	GJ/tonne CO ₂	-	3,49	3,49	3,49	3,49	3,49
EOP ¹	kWh / tncO ₂	-	292,58	140,99	173,99	140,99	185,15
GT efficiency				34,94	34,94	46,17	46,17
Marginal efficiency of gas				29,18	27,83	41,66	40,25

¹ A CO₂ compressor efficiency of 85% has been used to evaluate the total electricity output penalty and is consistent for all cases.

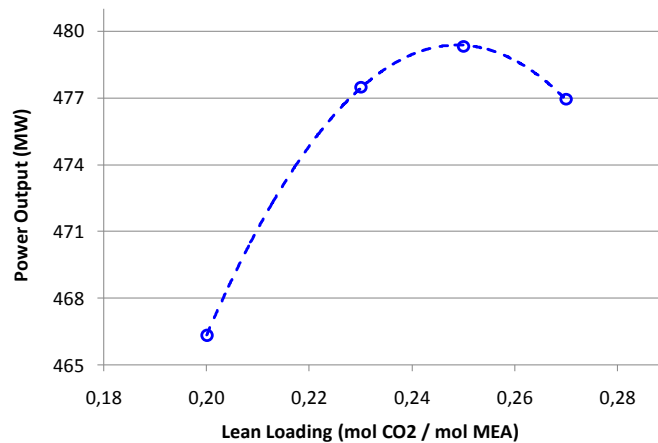


Figure 1.- Optimum MEA lean loading

3.2. Gas turbine heat matched retrofit with no access to the power cycle

For existing coal plants where there is lack of space for access to the power cycle or where the turbine hall foundation cannot support additional turbines, all the heat for the capture process is supplied from a natural gas CHP plant. Excess power would be exported from the site with this configuration. The GT is sized to match the heat requirement of the carbon capture process.

Two options are examined. A low capex low-efficiency option where the GT is combined with a single level pressure HRSG supplying the thermal energy required for solvent regeneration. It is important to note that there is a drawback in using a single pressure HRSG to supply the energy for solvent regeneration as it does not use the full potential for electricity generation from the natural gas calorific value. The second option uses a GT with a combined cycle to produce additional electricity.

The CC plant is either designed so that the total emissions from the plant meet an emission performance standard equivalent to an unabated CCGT, or it is designed to treat all the flue gas from the PC Power Plant.

Since the GT is sized to provide all the thermal energy of the carbon capture process the net power output of the site increases if the fuel input to the coal plant is kept constant. It is, however, possible to maintain the site output with the coal plant operated at a lower load. Table 1 summarises the most important parameters for comparing heat matched retrofit options.

3.3. Gas turbine power matched retrofit with access to the power cycle

Additional electrical power required for the capture process and to cover any loss in power output from the existing plant due to steam extractions is supplied by a CHP plant with the highest possible power to heat ratio for the fuel and the temperatures involved – power matching. The net electrical output from the site remains the same after CO₂ capture retrofit.

The CCGT provides the electrical power required for the capture process (compression and the ancillary power of capture system) and makes up for any loss in power output to restore the net power output of the plant. It is sized to match the power requirements of the carbon capture process.

Some heat for the capture process is recovered from the CCGT and the rest is provided by extraction from the existing steam cycle. The carbon capture plant is designed either to meet the emission performance standard of an unabated CCGT plant or to treat all the flue gas from the PC Power Plant. A separate carbon capture unit could also be added to the CCGT.

Further integration can be achieved by feeding the gas turbine flue gas to the existing coal boiler to increase CO₂ concentration of the flue gas and reduce the total volume of flue gas and the number of absorber trains. This option

is comparable to hotwindbox retrofit configurations sometimes proposed to repower existing coal plants with a combined cycle gas turbine. The gas turbine flue gas passes through a HRSG and is then fed to the windbox of the pulverized coal boiler to replace secondary air.

The HRSG is integrated with the steam cycle of the existing coal plant so that the gas CHP plant does not have a dedicated combined cycle.

When the PC Power Plant is retrofitted by introducing flue gas from the CCGT into the boiler furnace, the firing rate is reduced and, consequently, the steam production decreases. The HRSG supplies superheated to the boiler in order to maintain the steam production constant. Steam is supplied to both the superheater and reheater to maintain steam temperatures. The HRSG also produces LP saturated steam for solvent regeneration.

The optimum reboiler duty for the hotwindbox carbon capture retrofit was determined by conducting a sensitivity analysis of the effect of the lean loading on the reboiler duty and stripper pressure, the lean loading was varied from 0.20 to 0.27. The minimum reboiler duty (3.49 MW/kgCO₂) was found at 0.25 lean loading which corresponds to a stripper pressure of 1.817 bar as indicated in Figure 2 and Figure 3.

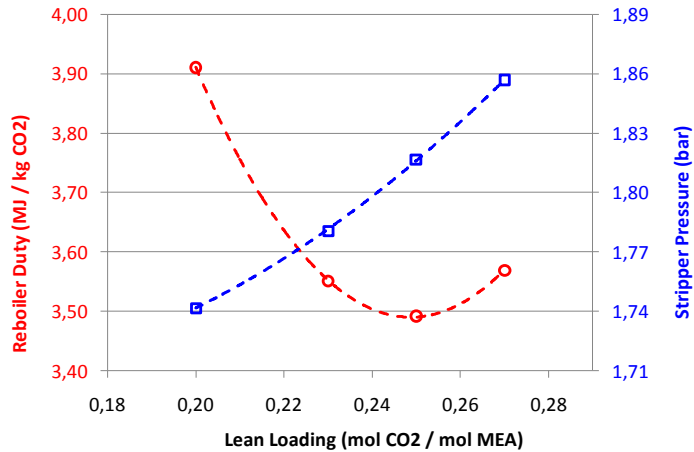


Figure 2.- Reboiler duty and stripper pressure dependence on the Lean Loading

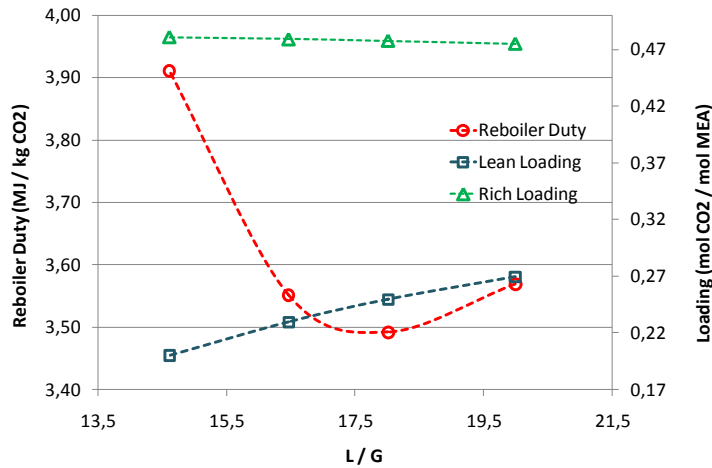


Figure 3.- Optimisation of solvent flow rate

It should be noted that the size of the CCGT depends on the energy requirements of the carbon capture process and on the amount of gas to be abated, if the power output of the site is kept constant.

Since the HRSG supplies superheated steam to the boiler the coal feed rate is reduced in proportions depending on the size of the existing coal, the performance of the carbon capture process and the overall capture level.

When the PC Power Plant is retrofitted by adding a CCGT to re-store the power output of the site the EOP highly depends on the carbon intensity of the fuel mix used in the plant, even when the reboiler duty per unit of CO₂ captured remains constant. The Carbon Intensity obviously depends on the ratio of coal to gas.

Figure 4 shows that the variation of the EOP is non-linear with the Carbon Intensity. The carbon intensity will effectively depend on the configuration of the existing site and vary from plant to plant.

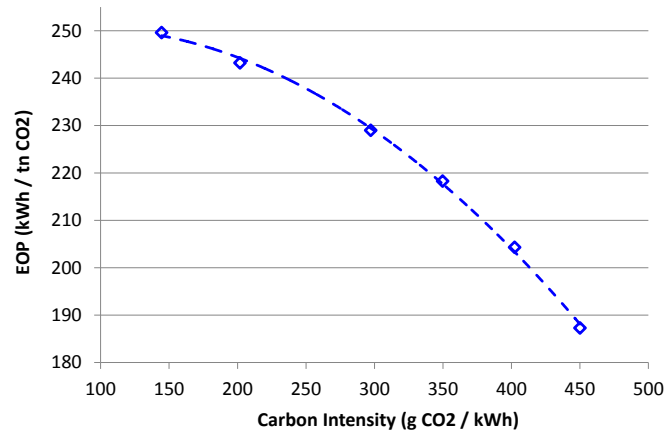


Figure 4.- Dependence of the EOP on the Carbon Intensity

In addition to the carbon intensity of the fuel mix, the EOP of the hotwindbox carbon capture retrofit depends on the CO₂ concentration of the flue gas and the amount of superheated steam supplied by the HRSG to the PC power plant.

The CO₂ concentration at the inlet of the carbon capture reaches 13% v/v, in comparison to 4% v/v at the exhaust gas of the turbine and 14% v/v for the coal plant with air-firing. Consequently, if the carbon emissions from the combustion of natural gas were to be captured, there is a benefit since the CO₂ concentration is closer to that of coal plant, as opposed to capturing from two streams at respectively 14% v/v and 4% v/v. On the other hand, as the HRSG generates large amount of superheated steam for the steam cycle of the existing coal plant, the production of LP steam is reduced in comparison to the other power matched retrofits and more steam has to be extracted from the existing steam turbines to supply the thermal heat for solvent regeneration

Figure 5 shows the steam cycle of the retrofitted PCPP with the addition of a CCGT and Figure 6 illustrates the integration of the HRSG and the steam cycle for a Hotwindbox Carbon Capture Retrofit.

The most relevant parameters for comparison of power matched retrofit are shown in Table 2.

Table 2.- Performance results of the fully integrated retrofit and power matched retrofits.

		POWER MATCHED RETROFIT					
		PC Power Plant	Integrated Retrofit	Unabated CCGT	Gas Standard CCGT	Fully abated CCGT	Hotwindbox Retrofit
<i>Retrofitted PC Power Plant</i>							
Coal thermal input	MWth	1517,93	1517,93	1517,93	1517,93	1517,93	1348,61
Gas thermal input	MWth	0,00	0,00	223,76	82,92	256,69	342,78
Power output	MWe	600,30	479,33	600,30	600,30	600,30	600,30
Carbon intensity of electricity generation	g CO ₂ / kWh	765,29	96,02	144,55	450,05	84,33	78,95
Overall efficiency	%	39,55	31,58	34,47	37,50	33,83	35,49
<i>Carbon Capture Plant</i>							
Lean loading		-	0,25	0,25	0,25	0,25	0,25
Carbon capture rate		-	90,00	90,00	90,00	90,00	90,00
Overall carbon capture rate		-	90,00	82,65	43,07	90,00	90,00
Total gas flow rate	kg/s	632,76	632,76	813,89	699,88	840,55	691,12
Gas flow rate to CC Plant	kg/s	-	632,76	632,76	312,76	632,76	691,12
Gas flow rate to Gas CC Plant		-	-	-	-	207,78	N/A
CO ₂ fraction to CC Plant	vol %	-	0,14	0,14	0,14	0,14	0,13
CO ₂ fraction to Gas CC Plant		-	-	-	-	0,04	N/A
Reboiler thermal heat	GJ/tonne CO ₂	-	3,49	3,49	3,49	3,49	3,49
Reboiler thermal heat of Gas CC Plant		-	-	-	-	4,10	N/A
EOP ²	kWh / tCO ₂	-	292,58	292,58	227,01	276,63	296,92
GT efficiency				54,06	55,95	49,10	52,87
Marginal efficiency of gas				54,06	55,95	47,13	51,16

² A CO₂ compressor efficiency of 85% has been used to evaluate the total electricity output penalty and is consistent for all cases.

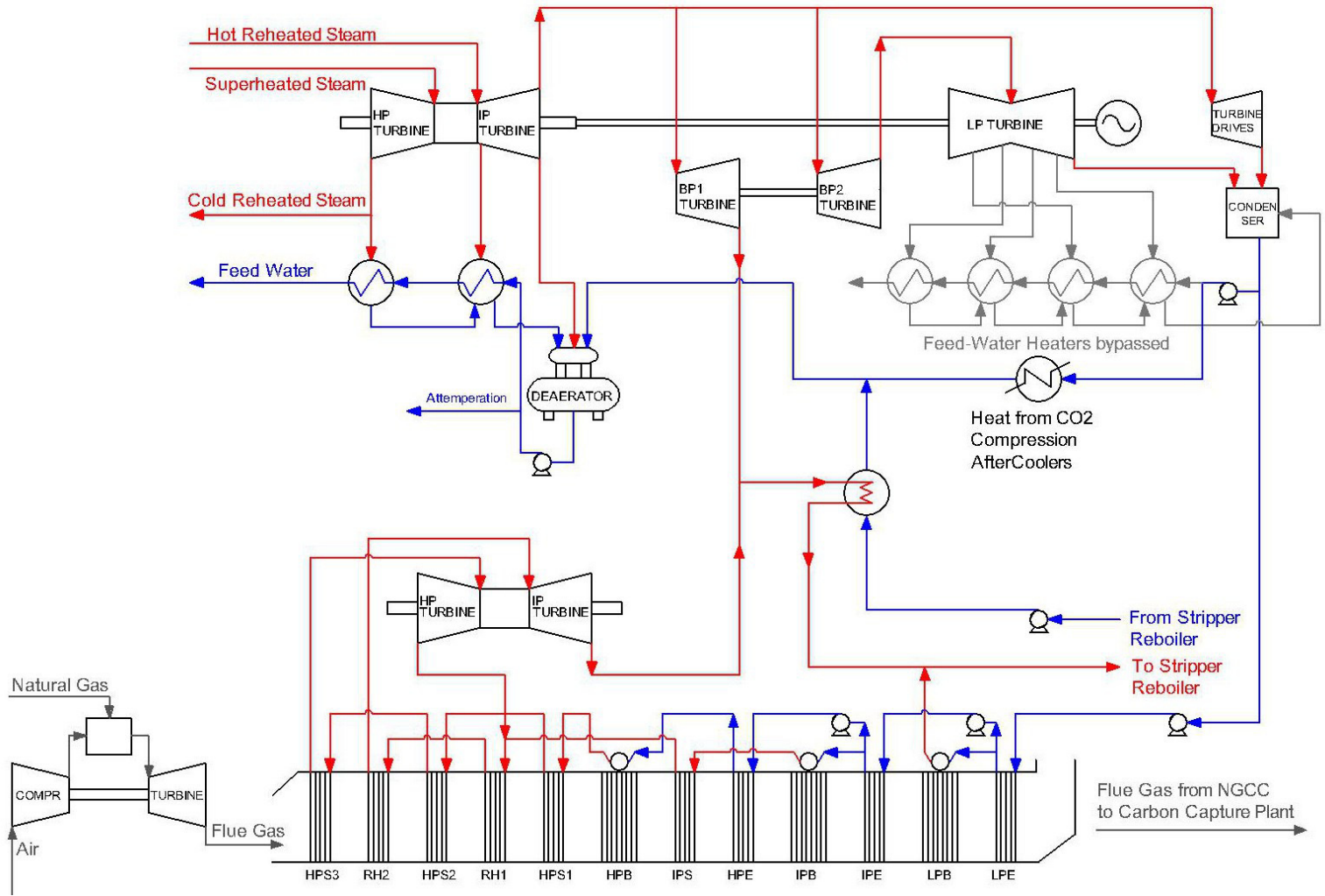


Figure 5.- Steam cycle of the retrofitted PC power plant with the addition of a CCGT

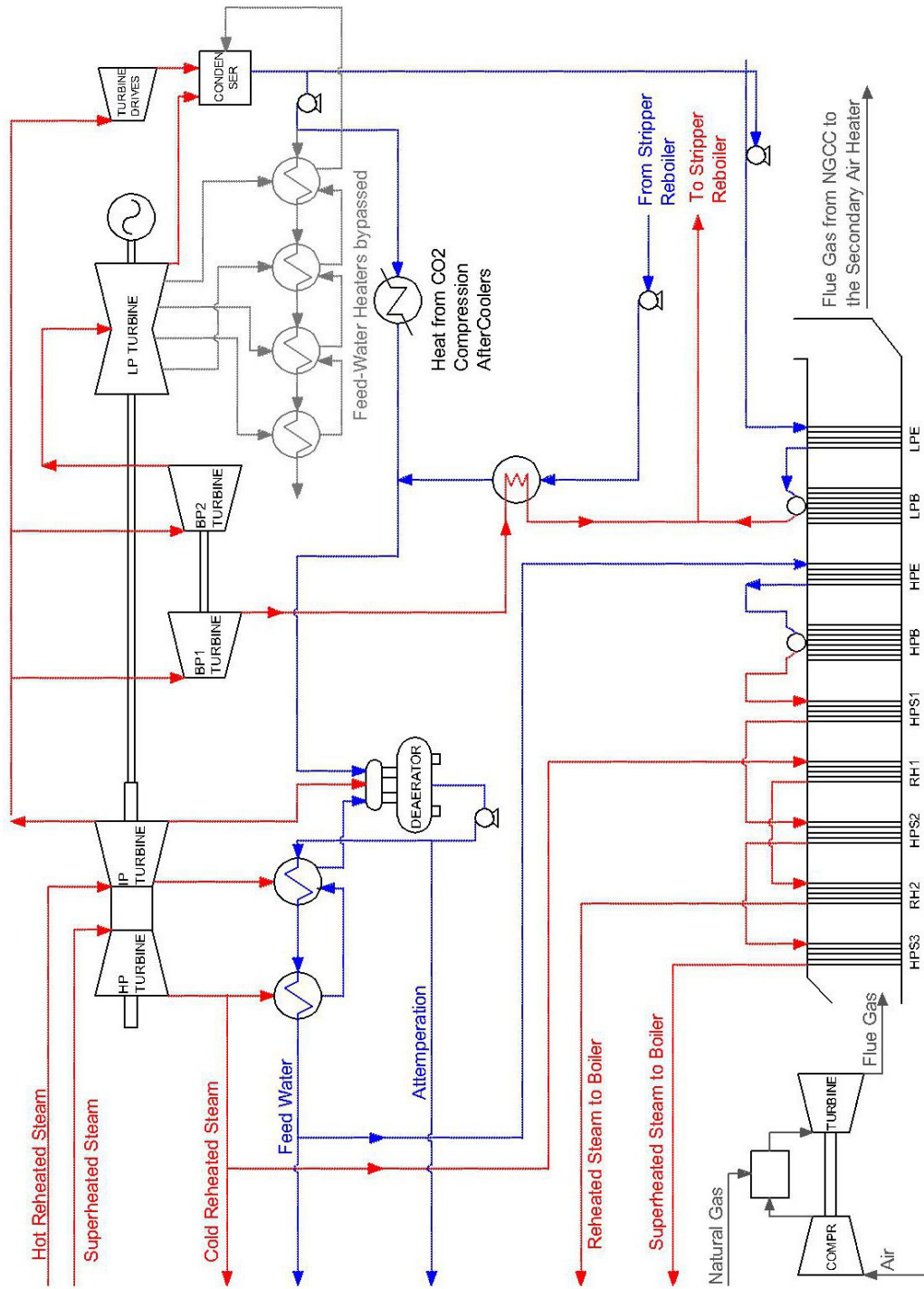


Figure 6. - Steam cycle of the Hotwindbox Carbon Capture Retrofit

4. Conclusions

- Retrofitting existing coal plants is expected to make an important contribution to the deployment of Carbon Capture and Storage. For existing plants with space and access to CO₂ storage, previous studies typically focus on configuration that reduces the output of the site resulting in a loss in revenue from electricity sales and, for base-load plants, underutilise a large fraction of the grid connection capacity. If demand for low-carbon electricity is going to increase, retrofit options that either maintain or increase the output of an existing site make the best use of the residual value of the existing asset.
- For many existing sites where there is lack of space for access to the power cycle and/or the foundation cannot support additional turbines, then, the simplest way to supply the electrical power required for the carbon capture process is adding a GT with a HRSG to supply steam to the carbon capture process. Although this option does not make use of the full potential of the natural gas calorific value it represents a low-risk retrofit approach.
- If there is no space restriction, a thermally efficient way to re-store the power output of the site when the PC power plant is retrofitted with CCS equipment is to integrate a CCGT with the power cycle of the site.
- This work reviews a range of options for CCS power project developers and examines the implication of capturing the carbon emissions from the additional gas usage, in the context of different regulatory regimes, a gas standard equivalent for coal plant emissions and higher capture levels around 90% to meet a carbon intensity of electricity generation in line with more ambitious CO₂ emission reduction scenarios.
- A novel retrofit option is proposed to maintain the output of an existing coal plant with a retrofit with capture and an additional gas CHP plant. Heat and power is supplied to the carbon capture process and superheated steam to the steam cycle of the retrofitted plant.

Carbon capture from both fuel sources is achieved in a single carbon capture unit by replacing the boiler secondary air with the gas CHP plant flue gas and by integrating the HRSG with the steam cycle of the existing unit. The CO₂ of the resulting flue gas is close to that of a coal plant, which would reduce the total volume of flue gas to be treated and the number of absorber trains. This and the absence of a dedicated steam cycle, can possibly result in significant capital cost savings. Further work will evaluate cost of electricity generation of this retrofit option.

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