AECOM

Immingham Combined Heat and Power (CHP) Plant

Environmental Permit Variation Application
Appendix E - Assessment of Best Available Techniques for Cooling

VPI Immingham LLP

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Quality information

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1. Introduction

1.1 Purpose of this Assessment

This appendix has been prepared by AECOM Limited (‘AECOM’) on behalf of VPI Immingham LLP (‘VPI’) and provides an assessment of the cooling options for the proposed Post-combustion Carbon Capture (‘PCC’) plants planned to be retrofitted at the Immingham Combined Heat and Power (CHP) Power Plant (‘the Installation’), operated by VPI under the Environmental Permit reference EPR/BJ8022IZ.

The purpose of this appendix is to determine which cooling technology represents Best Available Techniques (BAT) for the PCC plants when considering environmental, capital and operating costs against potential benefits for each cooling option, to support the Substantial Environmental Permit variation submitted to the Environment Agency (EA) to enable the PCC plants retrofit.

AECOM has prepared this BAT assessment using concept engineering information related to the initial design parameters of the PCC plants, available information about the local environment and the existing standards and guidelines presented in published guidance, including:

- EU Reference Document on the application of Best Available Techniques to Industrial Cooling Systems (‘Industrial Cooling BRef’) (December 2001);
- Environment Agency: Risk assessments for your environmental permit (April 2022); and
- Environment Agency Evidence Document SC070015/SR3 Cooling Water Options for the New Generation of Nuclear Power Stations in the UK (June 2010).

Although the latter of these documents is not directly related to the processes involved at the Installation, the EA have requested its use for BAT assessments for cooling options.

1.2 Background Information

The Installation currently consists of three Combined Cycle Gas Turbines (CCGTs), referred to as GT1, GT2 and GT3 and two Auxiliary Boilers. Currently the only cooling demand at the Installation is for the Steam Turbine Generator (STG) condensers. GT1 and GT2 were built in 2004, and the condensers are supplied with cooling water from a cooling tower. Blowdown from the cooling water circuit is held in the M1 holding pond, where it is tested in line with the Permit conditions and then pumped to the M2 holding pond prior to discharge to the South Killingholme drain via existing Emission Point W1.

GT3 was built at a later date (2009) and due to a lack of water availability, it was provided with direct air-cooled condensers.

As the existing combustion plant already has cooling systems in place, this BAT assessment is only concerned with the additional cooling required for the PCC plants.

It has been assumed for the retrofit of the PCC plants that there is potentially cooling water make-up available, and therefore the potential to utilise an open loop cooling water system has not been discounted on the basis of a lack of water availability. That said, it is understood that there remain constraints on water availability in the Humber region, including that the Humber Estuary is an internationally designated site and also that there is currently no outfall from the Installation suitable for the discharge of spent cooling water.

1.3 PCC Plants Description

VPI propose to retrofit two PCC plants to existing gas turbines GT1 and GT2 and the two Auxiliary Boilers at the Installation. The scope of the carbon capture project includes capturing approximately 95% of the carbon dioxide (CO_2) in the flue gas exiting GT1, GT2 and the two Auxiliary Boilers during continuous operation.

Each PCC plant will have a dedicated train of CO_2 compression integrated with oxygen removal and dehydration to achieve a pure CO_2 gas stream at 135 barg required for export to the CO_2 gathering network. It is intended that CO_2 will be exported at high pressure via an interface to a CO_2 gathering network adjacent to the Installation.

The water, steam and power required for the PCC plants will be supplied from the existing Installation.

The PCC plants will each have an associated Direct Contact Cooler (DCC), blower, absorber column (and associated flue gas stack), regenerator and cooling system, an integrally geared CO_2 compression facility including low pressure compression, oxygen removal, dehydration facilities and high-pressure compression. In addition, there will be a chemical store and storage tanks, surface water drainage system as well as ancillary plant, including cooling infrastructure.

A detailed description of the PCC plant to be installed is provided in Section 4.2 of the Main Supporting Document.

A number of options are potentially available to supply cooling to the PCC plants. These are presented and assessed in subsequent sections of this appendix.

1.4 Cooling Load Assessment

The main cooling requirements of the PCC plants are the DCCs and the main PCC plant facilities, where the majority of the heat rejection from the process occurs, and the CO_2 compressor intercoolers and aftercoolers; these equate to over 98% of total the cooling load for the new plant, with the remainder considered negligible and therefore not included in this assessment.

There are two potential operating modes for the PCC plants that form the basis for the assessment of the cooling loads:

- GT1 and GT2 operating at 100% load and both Auxiliary Boilers operating at 60% load (the ‘Design Case’), or
- GT1, GT2 and both Auxiliary Boilers operating at 100% load (the ‘Rating Case’).

The PCC plants will use cooling to lower the temperature of the flue gas coming from the GTs and Auxiliary Boilers, via a DCC, prior to amine stripping; the compression of CO_2 also generates heat and has an associated cooling requirement.

The combined cooling load associated with the Design Case is estimated to be approximately 260MWth, comprising a cooling load for the DCC, the water wash cooler, CO_2 stripper condenser and the lean amine cooler. The cooling loads for these plant items are shown in Table 1.1.

Table 1.1: Exchanger Duties for PCC plant (ISBL) per train

Plant/ equipment	Duty (MW)	Process Temperature (ºC)	
		In	Out
DCC	108 x 1.1	52.8	37.0
Water wash coolers	43.1 x 1.1	50.2	37.0
CO_2 Stripper condenser	43.1 x 1.2	95.8	40.0
Lean amine cooler	36 x 1.1	54.0	37.0

The compression system consists of an integrated geared compressor to provide low and high-pressure compression. The cooling loads for the CO_2 compressor systems have been estimated, and the cooling duties for open loop coolers, air-cooled and closed-loop water cooled system were found to only be marginally different, primarily due to the difference in the exchanger differential pressures and outlet temperature of the different cooling types. Additionally, there are small variations between the overall cooling load for the CO_2 compressors due to process differences. The cooling load for the CO_2 compressor system for the different cooling types assessed is shown in Table 1.2.

Table 1.2: CO_2 Compressor System Cooling Loads

Equipment		Cooling Load (MW)		
		Air-Cooled System	Once-through Cooling System	Closed Loop Water Cooled System
LP CO_2 Compressor	Interstage cooler 1	5.7	6.0	5.7
	Interstage cooler 2	5.3	4.5	5.3
	Interstage cooler 3	4.9	4.3	4.9
	LP CO_2 compressor aftercooler	5.3	4.4	5.3
HP CO_2 Compressor	Interstage cooler 1	2.3	2.3	2.3
	Interstage cooler 2	0.8	0.2	0.8
	HP CO_2 compressor aftercooler	14.8	14.3	14.8
Total		**39.1**	**36.0**	**39.1**
Closed loop air cooler (for CO_2 compressor intercoolers only)		N/A	N/A	19

The estimated cooling loads do not include a thermal or hydraulic margin, as a margin is understood to have been considered for the sizing of the heat exchangers to ensure sufficient margin of safety.

The cooling options include a review of both air-cooled and water-cooled systems. A number of options are available to supply cooling to the PCC plants; these are presented in Section 4 of this appendix.

2. Typical Industrial Cooling Systems

The Industrial Cooling BRef document describes the key typical cooling systems used for industrial installations as below:

- once through cooling systems;
- wet cooling systems;
- hybrid systems; and
- air-cooled systems.

A brief description of these technologies is provided in the following sections.

2.1 Once-Through Cooling (Direct and Indirect)

Once-through cooling (OTC) uses water pumped from a controlled water (such as an estuary, river or other surface water feature) via a large water inlet, directly in a heat exchanger or condenser, after which the heated water is discharged directly back into a surface water body (either the same as the source or a different body). OTC is typically used where large cooling capacities (>1,000MWe) are required.

OTC systems involve significant water requirement, with the Industrial Cooling BRef document stating that such cooling systems can consume up to 86t/h/MW_{th} of water. OTC can be used either as a direct cooling medium, passing through a heat-exchanger with the stream to be cooled, or as an indirect cooling medium where a secondary heat-exchanger and recirculating cooling fluid are used (typically where there is a high environmental risk if the cooling water gets contaminated). Indirect OTC cooling is less efficient than direct cooling due to this secondary heat-exchange process, and therefore has not been considered further in this assessment.

OTC systems are affected by the availability of sufficient surface water and the water quality, as well as discharge limitations, for example, the effect of the thermal load on the receiving water body and its ecological sensitivity. As all the cooling water used in OTC systems is usually discharged (rather than being recirculated), it typically undergoes only mechanical screening and coarse filtration to prevent damage to downstream equipment so that there is no change in water chemistry between the circulating water and the source water.

Scale deposition of biological fouling is a common issue with OTC systems and if the water is particularly corrosive (i.e. sea water or estuarine water as would be the case if utilised for the VPI PCC plants) the impact on material costs can be significant.

Other environmental considerations include:

- the use of energy for pumping;
- the risk of entrainment or impingement of eels and/ or other fish;
- bio-fouling, scaling or corrosion; and
- the use and subsequent discharge of additives to the controlled water (receiving water body).

In addition, to minimise sediment entrainment, a forebay structure may be required and to ensure sufficient head of water to reach the plant, intake tunnels may be required at depth. If required, these add further capital cost and maintenance obligations.

It is recognised that the EA typically considers direct OTC as representing BAT for thermal generation plants located in close proximity to a coastal or estuarine water source, since, in theory there is sufficient water available in such locations, resulting in maximisation of the thermal efficiency of the system. However, other cooling options can also represent BAT based on site-specific considerations and the type of plant being cooled.

2.2 Wet Cooling Towers

Wet cooling towers use water as the main cooling medium with the heat lost through contact with air. The heat load in the cooling water is removed by evaporation within a cooling tower and the cooled water is recirculated within the system, typically via a reservoir (cooling tower basin). A small amount of cooling water is lost through evaporation and drift (entrainment of droplets), and the cooling water is refreshed after several cycles of concentration, through blow-down of a proportion of the stream, to maintain quality. Water is added to compensate for the blowdown and evaporation losses; this is referred to as 'make-up' water.

Cooling water from the process is pumped to the top of the cooling tower and the water is distributed, by spray, over the cooling tower packing, to maximise the contact with air flow though the packing.

Drift eliminators are employed at the top of the tower to minimise the entrainment of water droplets within the air flow. The air exiting the tower will be saturated with water, and therefore visible plumes will frequently occur as the warm air mixes with colder atmospheric air causing condensation of the water vapour. The extent of the plume formation is dependent on weather conditions, with colder or more humid air resulting in larger plumes.

Several alternative designs for the water-air evaporative cooling stage can be employed, including:

- natural-draught air flow, which relies on a pressure differential between top and bottom of the tower, generated by the change in the density of the air, to induce a draught of air up the tower in a counter-flow to the cooling water; and
- mechanical-draught air flow, which uses mechanically generated air flow using fans either at the top (induced-draught) or bottom (forced draught) of the tower; within these systems the air flow can be perpendicular to the water flow (cross-current) or in the opposite direction to the water flow (counter-current).

2.2.1 Natural Draft Towers

Natural draught towers are made from reinforced concrete and may be large structures of significant height; and incur high capital investments. They can emit continuous visible plumes when operational and therefore can present significant visual impact. They also have a significant potential for plume grounding and the risk of icing of roads during certain weather conditions. Natural draught towers are best suited for areas of high relative humidity.

Natural draught towers are not considered to be appropriate for the PCC plants due to efficiency issues arising from typically lower relative air humidity at the location, lack of cost effectiveness for the cooling duty required, the space requirements for the towers on site and the visual impact of potential visible plumes and the towers themselves. The use of natural draught cooling towers has therefore been discounted from this assessment.

2.2.2 Mechanical Draft Towers

Mechanical draught towers are typically smaller than natural draught towers, and therefore the capital investment is lower. However, the use of mechanical fans to drive air flow represents a parasitic load on the process and can also generate additional noise emissions. Mechanical draught systems also produce visible plumes, albeit at lower height than for natural draught systems due to comparatively lower tower exit height. The impacts from visible plumes depend on the proximity and sight-lines of nearby receptors.

The make-up water can be drawn from saline or non-saline sources, but in both cases, the water intake system needs to be protected from organic growth to prevent blockages. Disinfection processes (e.g. chlorination) can be employed, although this has a potential environmental impact from the discharge; alternatively, thermal treatment can be employed although this is more complicated to operate and may affect the overall thermal efficiency of the Installation. Where saline water is used, the material of construction for heat-exchangers must be able to withstand the more corrosive effects from salinity and therefore require higher capital expenditure (CapEx).

Wet cooling towers are typically not suitable for plants located in close proximity to transport routes or residential receptors due to their high visual impact from high cooling towers and tendency to produce large visual plumes which can result in overshadowing of property and ice formation on roads in certain conditions.

2.3 Air-Cooling

Air-cooling is provided by passing a cooling flow of air over finned tubes within a bank of condensing heat exchangers which contain the medium to be cooled (typically steam). These banks of heat exchangers are normally mounted in an elevated structure to allow good and even air flow across the heat exchange surfaces; the air flow is created by large fans.

Dry Air Cooled Condensers (ACC) circulate the process stream (typically steam) through the heat exchanger, whereas indirect ACCs circulates a secondary cooling medium (typically water) through the heat-exchanger and this returns to cool the process stream via a condenser.

The heat-transfer characteristics of the air-cooled heat exchangers, and the fact that the air temperature is normally higher than water-cooled options, means that this is typically the least favourable arrangement for thermal generation plant efficiency. However, air-cooling requires no off-site infrastructure as they rely solely on the supply of electrical energy to operate the fans. Whilst this can represent a more substantial parasitic load than some cooling options, there is no requirement to pump cooling water.

These systems are best suited for locations with a consistently high relative humidity, with efficiency decreasing with lower relative humidity levels. They are also suitable in water constrained areas and where the cooling duty is not linked to combustion.

Air-cooling has the disadvantage of the noise generated by the fans and the larger footprint required to achieve the necessary level of cooling. However, it offers benefits in other areas such as avoiding the environmental impacts associated with water abstraction and discharge as well as the construction effects of the associated pipework infrastructure; and heat is discharged directly to the air without the generation of visible plumes created by wet methods.

2.4 Hybrid (‘Wet-Dry’) Cooling

Hybrid cooling (also known as plume-abated mechanical draft cooling) uses a combination of dry air cooling and evaporative cooling methods.

The cooling water is first dry-cooled, by passing through tube banks in the hybrid cooling towers over which air is drawn by forced draught fans; the cooling water then passes to a wet cooling stage where it is sprayed over packed bed elements, to provide an extended, and therefore more efficient, air/ water contact surface area. In the wet cooling stage, the water is cooled by two effects: the direct contact of the cold air flow with the water, and the cooling effect of the evaporation of a small proportion of the water.

This method of cooling is slightly more efficient than air-cooling as it benefits from the more efficient water-cooled heat exchange characteristics but still relies on the ambient air conditions to achieve some cooling. Due to the application of air cooling, the water demand for these cooling systems is lower than that for fully wet systems.

Hybrid tower systems are comparable in size to mechanical draught cooling towers. However, the additional fans result in a higher associated auxiliary power load and greater noise generation than fully wet cooling methods. In common with air-cooling, noise generation from fans may be higher than from fully wet-cooling methods, however, the footprint of hybrid towers is smaller than air-cooling as a result of the efficiency of the wet-cooling section.

The hybrid tower system requires make-up water to compensate the losses through evaporation and the purge of concentrated salts in the recirculated water; however, the water consumption is circa 25% of that for wet cooling systems. The Industrial Cooling BRef document states that the consumption of water for an open hybrid tower is typically around $0.5 m^3/h/MW_{th}$.

Hybrid cooling towers can intermittently generate visible plumes of water vapour under certain weather conditions, in particular during cold or humid weather, however the incidence of such plumes is significantly less than for fully wet-cooling systems as the evaporated water is heated (thus increasing the saturated vapour pressure of water in the emission from the hybrid tower) as the vapour passes across the dry cooled section.

Hybrid cooling has higher CapEx and parasitic loading than fully wet systems. However, hybrid cooling may represent BAT where plume-abatement and visual impact of tall towers or visible plumes are considered important.

3. Existing Environment

3.1 Overview

This section describes the environmental context for the PCC plants, in particular the local environment with the potential to be impacted by the cooling options under consideration.

The VPI Immingham CHP Power Plant lies 1.7 km north of Immingham and 1.5 km west of the Humber Estuary. The Installation is located within the administrative boundary of the North Lincolnshire Council. The PCC plant area lies directly to the south and south-east of the existing Installation on a parcel of vacant land (approximately 8.8 ha) which currently comprises areas of hardstanding, existing below ground utilities and grassland with an open ditch running through the centre. The area was previously used for laydown during the construction of the existing VPI Immingham CHP Power Plant.

With the exception of some small areas, the entirely of the Installation site lies within Flood Zone 3 and is therefore classified as having a ‘high risk’ of flooding from fluvial or tidal sources.

A number of environmental receptors have been identified in the vicinity of the Installation. All distances are given as the shortest distance between the receptor and the closest point of the PCC plants.

3.2 Residential Receptors

The Installation is situated in a heavily industrialised area with limited residential receptors within close proximity.

There is a single isolated residential property on Marsh Lane approximately 330 m east of the Installation and other residential properties within 1-2 km to the west in the villages of South and North Killingholme and 1.7 km south in Immingham.

3.3 Ecological Receptors

The Humber Estuary SSSI/ SPA/ SAC/ Ramsar site is located approximately 1.3 km northeast of the Installation (at its nearest point). The Humber Estuary includes a range of coastal habitats (such as mud and salt flats, lagoons, salt marshes and coastal sand dunes), which provide feeding and roosting opportunities for important numbers of waterbirds in the non-breeding season. North Killingholme Haven Pits SSSI is located approximately 2.2 km north of the Installation.

There are no other European sites within 15 km of the Installation.

There are seven locally designated sites within 2 km of the Installation, with the closest being Rosper Road Pools Local Wildlife Site (LWS) 100 m to the east of the Installation (at its nearest point).

3.4 Key Considerations

Nearby residential receptors are considered to be the most sensitive receptors to visual and noise impacts from the cooling options for the PCC plants. The internationally designated ecological receptor (Humber estuary) is considered to be the most sensitive to water impacts from the cooling options. Potentially significant impacts would be:

- the abstraction of estuarine water, with mitigation required to avoid entrainment of aquatic organisms;
- impacts on estuarine water chemistry and biodiversity from the discharge of water with thermal plume and potential water treatment chemicals, requiring mitigation in the form of treatment prior to discharge, and specific discharge requirements;
- visual impact of evaporative water plumes (visible plumes) from cooling towers, and cooling towers themselves, on adjacent and nearby residential receptors;
- noise from pumps or fans with mitigation required to avoid impacts on local residential receptors; and
- temporary construction impacts from installation of additional intake and outfall pipework.

4. Cooling Options for the VPI PCC Plants

4.1 Overview

The selected PCC plant technology does not result in different cooling loads for the summer and winter operation of the PCC plants.

There is no spare capacity available from the existing GT1, GT2 and Auxiliary Boilers cooling towers for the PCC plants. During the summer, all of the available cells within the cooling towers are utilised by the operation of GT1, GT2 and the Auxiliary Boilers. Although capacity will be freed up due to reduction in condenser load when the PCC plants are online, there will be no free capacity when the PCC plants are offline, and steam is diverted to the steam turbine, or when the Auxiliary Boilers are used to increase steam supply.

The assessment therefore includes consideration of the overall cooling duty of each option, water consumption, water source and necessary treatment, parasitic energy load and capital costs for equipment, pipework and intake and outfall upgrades.

The following options have been considered for the cooling options BAT assessment for the PCC plants:

- Option A - Wet cooling tower (Indirect) system;
- Option B - Dry air-cooling system;
- Option C - Once–through cooling (Open loop wet cooling) system;
- Option D – Hybrid system (water and air coolers sharing the duties);
  - D1 – minimum water make-up;
  - D2i – air cooled PCC plants, open loop water cooled CO_2 compressor;
  - D2ii – air cooled PCC plants, closed loop water cooled CO_2 compressor; and
  - D3 – water cooled PCC plants, air cooled CO_2 compressor.

Indirect cooling in Option A consists of mechanical draught towers.

The assessment of available cooling techniques is based on the cooling conditions shown in Table 4.1 below.

Table 4.1: Process Design Details Used for the Assessment of Cooling Systems

Process Parameter	Value
Design dry bulb temperature	23°C
Design wet bulb temperature	17.5°C
Minimum exchanger approach	10°C ΔT
Open loop cooling water supply temp	25°C
Fouling factor	0.00035 K.m^2/W (cooling water service)
CO_2 compressor discharge pressure	138 barg

The CO_2 compressor intercooler temperatures and efficiency are assumed to be the same for both closed loop water and air-cooling, although in reality the water cooling will likely be a slightly warmer. Once the compressor vendor is confirmed, the particulars of the system may vary, but should not affect the outcome of this assessment.

The assessment also includes a hot air re-circulation margin of 1°C on ambient design temperature (23 °C) for air coolers, therefore providing a design air temperature of 24°C.

4.2 Description of Options Considered

An assessment of potential cooling options for the PCC plants has been carried out to evaluate the techniques, or combinations thereof, that could be applied to the PCC plants. A summary of the assessed options is provided in the following sections.

4.2.1 Option A – Wet Cooling Tower (Indirect)

This option considers the use of a closed loop water-cooled system to cool the process, with the use of air coolers proposed for cooling the return water in the circuit. The cooling water is usually dosed with corrosion inhibitor and glycol to reduce scale and protect from winter conditions respectively. Large cooling water circulation pumps will potentially be required to move the cooling water around the circuit.

This option was discounted from further assessment for the PCC plants due to difficulty in reaching the required PCC plant process temperature of 37 °C due to the two temperature approaches across the exchangers in series, as is shown in Table 4.2.

Table 4.2: Cooling Process Temperatures for Option A

Process Parameter	Temperature
Design air temperature based on maximum dry bulb temperature (26.6 °C + 1°C hot air recirculation)	28°C
Minimum temperature approach for air/ cooling water coolers	10°C
Cooling water temperature (design air temperature + approach)	38°C
Minimum temperature approach for water/ process coolers	5°C
Minimum process cooling temperature (cooling water temperature + approach)	43°C

The minimum process cooling temperature of 43°C is higher than the required PCC plant process temperature of 37°C. It is therefore considered that this option is not viable.

4.2.2 Option B – Dry Air-cooling

This option proposes cooling the process with direct air-cooling using fin fan coolers. The PCC plants would require connecting to multiple banks of air coolers and cooled with ambient air.

The air-cooler system has a suitable design air temperature (23°C + 1°C) allowing the achievement of the required process temperature of 37°C.

Air-cooling can potentially lead to larger diurnal and seasonal temperature cycles, however no additional systems are required to control this cooling method as the process output can be controlled directly by switching off or turning down the fans. During colder ambient temperature the fans will switch off entirely. Overcooling/ winterisation will need to be reviewed with hot air recirculation or steam coils to heat the incoming air as required.

This design requires no water systems, therefore has no water make-up requirements, no large cooling medium pumps and no water treatment dosing, making it easier to operate. The larger quantity of fans provides a high reliability and availability for cooling. Should a single fan/ motor assembly fail, it will have a minimal effect on the overall performance of the air cooler.

Air cooling systems can typically be easily designed to withstand higher pressures. They also have a low potential for the process to leak into the cooling media system.

The larger plot space of air cooler banks provides difficulties with layout; however, the increased plot requirement could be offset with potentially locating other equipment underneath the Air-cooler system.

The proximity of the air coolers can give a potential for hot air recirculation, which could potentially be mitigated by:

- orientating the air coolers with the typical prevailing wind direction;

- increasing the distance between the air coolers (plot permitting); and/ or
- reduce effect of obstructions (DCC, stripper, etc) by appropriate positioning of the air-coolers.

It should be noted that the non-compressor coolers have a much lower air outlet temperature further reducing the impact of hot air recirculation.

4.2.3 Option C – Once Through Cooling

This option utilises a once-through cooling (OTC) system with an open water-cooling loop. The cooling water return is cooled using a cooling tower to provide the heat rejection from the system. The cooling tower relies on evaporation of water to approach the wet bulb air temperature.

Cooling water is required to be dosed with corrosion inhibitor and glycol to reduce scale and protect from winter impacts (winterisation) respectively. The open loop water system needs further treatment to avoid microbial growth including legionella. The water system also needs to be regularly monitored to maintain optimal and safe operation.

This system has large scale infrastructure requirements, comprising large cooling water circulation pumps and network of pipes, to move the cooling water around the circuit. Using the estimated cooling duty, the water requirement for recirculation within the cooling system has been estimated to be 49,060m^3/hr. In addition, this cooling system would require make-up water, estimated to be 938m^3/hr on the basis of evaporation loss, drift loss and blowdown requirements.

Publicly available data indicates that there is already significant pressure on water use in the Humber region from multiple users and there are constraints for water use in the region. Water use is likely to limit deployment of water intensive technologies as there will be limitations on supply from surface and ground water sources. Damage to the environment from unsustainable abstraction, as well as thermal discharge plumes from cooling water, cause eutrophication and must be limited to reduce the impact on the environment. This option is therefore very likely to adversely impact the local environment.

This option has the advantage of utilising wet bulb temperature giving a cooling water supply temperature of 25°C. The minimum approach temperature for open loop water coolers can go as low as 5°C, if benefits can be seen using 30°C process temperature. Furthermore, lowering compressor inlet temperatures could potentially increase compressor efficiency.

Once through water cooled systems usually have a lower pressure drop than air coolers on the process side. On the compressors, if the intercoolers are all water cooled, this could enable power saving from the compressor shaft. CO_2 is to be compressed from atmospheric pressure to 138barg, so the stage compression ratios are key.

The cooling tower and pumps could potentially be located in the common area to assist plot layout, although the cooling tower is still a substantial piece of equipment. Water make-up is required due to the evaporative, drift and blowdown losses. All the extra equipment makes this system harder to maintain and control compared to the air-cooled option.

Due to the temperature fluctuations within the cooling system from start up to maximum load, the water will expand and contract. An expansion drum is therefore required to allow the volume of the water to change, and avoid a loss of containment.

4.2.4 Option D – Hybrid Cooling System

This option utilises both direct air cooling with air coolers and open (or closed loop for the CO_2 compressor) water cooled loop to cool the process. The main advantage of this option is that potentially the Installation's existing open loop water cooling system (part of the existing hybrid cooling system for GT1 and GT2) could be extended, rather than building an entirely new system

Closed loop water cooling was only reviewed for the CO_2 compressor due to the inability to reach the PCC plants process temperature.

Since the CO_2 compressors are not as sensitive to process temperatures, a closed loop water cooling system could be used. So, a hybrid option for only the compressor to be closed loop water cooled has also been reviewed (see sections 4.2.4.2 and 4.2.4.3).

4.2.4.1 D1 – Open Loop Water Cooled with Minimum Water Make-Up

This option only considers the application of the water-cooling system to provide for limited cooling duties, so as to minimise make up water requirement.

The equipment modelled as water cooled were:

- LP CO_2 compressor 1st stage interstage cooler (to have a lower differential pressure (ΔP) in the exchanger);
- LP CO_2 compressor final (3rd) stage interstage cooler (the lower 30°C process temperature); and
- HP CO_2 compressor after cooler (the lower 30°C process temperature).

The water recirculation rate was calculated to be 4,427m³/hr using the duties detailed in Table 1.2. The make-up water was calculated as being 85m³/hr.

This was noted to be able to achieve the minimum cooling water use (and therefore make-up) and gives the option to extend the current facilities with minimal additional equipment.

4.2.4.2 D2i – Air Cooled PCC Plants, Open Loop Water Cooled CO_2 Compressor

This option applies a hybrid approach, whereby the cooling duty for the PCC plants would be provided by an air-cooled system whilst only the CO_2 compressor will have open loop water cooling.

The water recirculation rate was calculated to be 6,720m³/hr whilst the make-up water was calculated to be 129m³/hr.

4.2.4.3 D2ii – Air Cooled PCC Plants, Closed Loop Water Cooled CO_2 Compressor

This option applies air cooling to the PCC plants and closed loop water cooling to the CO_2 compressors. The lowest process temperature achievable is 39°C due to the two exchanger approach temperatures which are, air to cooling water (+10°C) and cooling water to process (+5°C). Therefore, it is required to use a closed loop air cooler (for CO_2 compressor intercoolers only) in this cooling option, having additional cooling load.

The water recirculation rate was calculated to be 6,720m³/hr, however, no make-up water is required due to closed water loop.

4.2.4.4 D3 – Open Loop Water Cooled PCC plants, Air Cooled CO_2 Compressor

This option uses the largest cooling water load for the PCC plants whilst applying air cooling to the other cooling loads.

The water recirculation rate was calculated to be 42,863m³/hr whilst the make-up water was calculated to be 820 m³/hr.

4.3 Assessment of Available Options

4.3.1 Compliance with Operating Requirements

All options except Option A meet operating requirements of providing cooling to the process to the desired temperature, and therefore Option A has been discounted from further consideration as it would not meet the process requirements.

4.3.2 Land Availability

The footprint of each cooling option under consideration has been reviewed.

Option D (Hybrid) – D1 has the minimum water-cooling requirement and consequently minimum water make-up; therefore, only three CO_2 compressor coolers would be open loop water cooled in this option resulting in maximum process benefits. This results in this option requiring a very similar area to Option B (air-cooling).

Option D2i comprises air-cooling for the PCC plants whilst the rest of the plant will be open loop water cooled, meaning a combination of the air-cooled main exchangers (as Option B) and the open loop water cooled heat exchangers (as Option C) will be implemented. The multiple air-cooled compressor intercoolers are expected to take up less space than the common water-air cooler (like in Option D2ii).

Although the duty of the five intercoolers required for Option D2i is similar to the duty of the single water cooler, the area is larger due to the smaller temperature difference.

The closed loop water cooled CO_2 compressor required in Option D2ii might have slightly higher process temperatures during summer peak temperatures, however, it is not considered to drastically change the compressor efficiency and therefore will not affect shaft power. Option D2ii has air cooling for the PCC plants whilst the rest of the process employs open loop water cooling. This uses the air-cooled main exchangers with the closed loop heat exchangers for the CO_2 compressor coolers. This option would require a larger footprint than the air cooled (Option D2i) but it should be noted that there are fewer pipe runs to and from the air coolers. This option has several opportunities for reducing the plot space requirement for the PCC plants to optimise the plot area.

Option D3 has open loop water cooled PCC plants with the remaining plant being air cooled. This uses the water-cooled main exchangers with the remaining heat exchangers being open loop water cooled. This option has a large PCC plant duty and therefore needs a cooling tower installation (albeit smaller than the cooling tower for Option C).

There is a potential for Options D1 and D3 to be installed as expansions to the existing cooling water system at the Installation.

The main advantage of water-cooled options is that less piping is needed. Water coolers have a lower pressure drop than air coolers on the process side, so if the intercoolers are all water cooled, this is expected to result in energy savings. CO_2 is to be compressed from atmospheric pressure to 138barg as part of the process, so the staged compression ratios are key. The closed loop air cooler and pumps for Option D2ii can be located in the common area to assist plot layout. The water-cooled exchanger will need to be periodically cleaned, so the tube bundles will need to be pulled out to allow this.

The estimated land-take for each of the options under consideration (Options B, C, D1, D2i and D2ii, and D3) is shown below in Table 4.3.

Table 4.3: Estimated Footprint for Each Cooling Option

Cooling System Component	Associated Footprint (m^2)					
	Option B	Option C	Option D1	Option D2i	Option D2ii	Option D3
CCU exchangers	4,003	178	4,003	4,003	4,003	178
CO_2 compressor	467	17	221	17	17	467
Cooling tower (1)	0	2,350	260	520	0	2,050
KO drums on CO_2 compressor	100	0	60	0	0	100
Total Footprint	**4,570**	**2,545**	**4,545**	**4,540**	**4,020**	**2,795**

Notes:

[1] Cooling tower includes circulating pumps, piping etc.

4.3.3 Constructability

Option B would involve installing air coolers (with intercoolers requiring an area of $286m^2$ and aftercoolers requiring an area of $181m^2$), requiring large foundations. Although Options D1 and D2i are estimated to have a comparable footprint to Option B, the area required for the air-coolers for these options is lower than Option B (intercoolers for Option D1 being $204m^2$ and $0m^2$ for Option D2i (intercooler being integral to the compressor) and $17m^2$ for aftercoolers for both options). Option B would also require appropriate piping manifold design.

Option C would require a large cooling tower, with multiple large cooling water recirculation pumps, suction basin and a large foundation to handle cooling tower size. Make-up and dosing facilities for the circulating water will also be required. There would be a reduction in construction around the CO_2 compressor design, compared to Option B, as the package includes integral water coolers and knock out drums.

Hybrid Options D1 to D3, all have a mixture of the constructability issues outlined for Options B and C above.

4.3.4 Capital Expenditure

The preliminary capital expenditure (CapEx) figures for each of the Options assessed are based on initial data from the solvent licensor and compressor vendors. As such, only the costs that relate to the systems that are different across the options have been considered for this assessment, and therefore do not present the total cost of the Options.

The CapEx for the Options is dependent on the materials selected/ required for efficient operation of the PCC plants; for instance, the low-pressure intercoolers will be stainless steel due to the presence of wet CO_2 in the low pressure section of the compressor, whilst the high pressure compressor CO_2 section will be carbon steel as it will only handle dried CO_2.

Table 4.4 provides the indicative total CapEx breakdown for the options. The CapEx costs include the cost for the procurement and construction of various components of the PCC plants, including but not limited to, heat exchangers, CO_2 compressor coolers and cooling tower(s). As these costs are indicative at this stage, details of anticipated costs for each component are not provided, although an estimated total CapEx cost is provided to allow comparison of the options being assessed.

Table 4.4: Indicative CapEx for the Cooling Options for the PCC plants

Option	Indicative CapEx (£ million (+/- 50%))
Option B	132
Option C	152
Option D1	145
Option D2i	150
Option D2ii	152
Option D3	140

As shown in Table 4.4, Options C and D2ii are expected to have the highest associated CapEx, primarily due to the relatively higher costs for the installation of CO_2 compressors.

Option B is shown to have the lowest CapEx as it does not require cooling towers or associated pumps, which comprise a significant proportion of the CapEx for wet cooling options, with the highest costs for these components expected to be for Options C and D3 due to the large wet cooling system.

The main proportion of the CapEx for the options is associated with the heat exchangers and CO_2 compressors. The CO_2 compressor costs for all water-cooled options include interstage water coolers with integral knock out drums, and therefore have a related cost for air cooled options (Options B, D1 and D3) albeit this is a relatively small cost compared to the overall capital cost for these options.

4.3.5 Operational Costs

The operational expenditure (OPEX) calculations for all options are based on the PCC plants operating for 8,760 hours per year with a 95% availability.

Previous operational experience has demonstrated air cooler fans (Option B) to have an efficiency of 75% whereas pumping power includes 5% motor losses (Option C), however, both options require additional power for the additional air cooler pressure drop in the CO_2 compressor. Option C will comprise pumps to maintain a constant flow of the water in the cooling circuit, resulting in a colder cooling water return temperature but with a lower duty.

Option D2i and ii have a lower compressor shaft power required for the water-cooled option (due to the lower ΔP for the water coolers). This may be slightly offset if the compressor interstage temperatures are higher, however, this will be limited to the hottest period of the year during daytime. The closed loop cooling Option 2Dii has the benefit of no makeup water, therefore having the lowest parasitic load.

Table 4.5 shows the parasitic load of the different PCC plant cooling options, with Option D3 having the highest parasitic load and option D2i having the lowest parasitic load. Option B has very similar energy usage as water cooled methods Option C and Option D1, and therefore can be considered to be as efficient as there water cooled options.

Table 4.5: Indicative Electrical Usage for the Available Cooling Options

Option	Electrical Use (MWe)
Option B	10.3
Option C	10.1
Option D1	10.1
Option D2i	7.3
Option D2ii	7.8
Option D3	13.1

Table 4.6 gives the OPEX breakdown of the options. As with the capital costs, the operational costs are only indicative at this stage and therefore only the relative difference between the operational costs/ components of the options has been shown.

Table 4.6: Indicative Relative OPEX for the Available Cooling Options

Option	Total OPEX / year (£ million /yr)
Option B	4.2
Option C	9.8
Option D1	4.6
Option D2i	3.7
Option D2ii	3.1
Option D3	10.4

The water generated in the PCC plants (Options D2i and D2ii) is expected to be able to offset the amount of water required. If the amount of water generated is larger than required, the excess water can be used to offset the current Installation's use.

4.3.6 Engineering and Design Effort

There is no major differentiator between the level of engineering and design effort for the different options because the overall quantity of equipment associated with each option is similar; however, the pumps related to the water-cooled options have additional civil and structural, electrical and instrumentation requirements. This is however partially offset by the additional knock-out drums required for the air-cooled option.

The air-cooled options are likely to have relatively minor maintenance requirements compared to water-cooled options; for instance, the pumps used in the water-cooled options will need regular maintenance as will the circulating water. Furthermore, water cooled options will require installation of spare pumps, unlike the air coolers, due to the increased chance of failure of rotating equipment and maintenance. The water-cooled systems will need to be winterised to deal with low ambient temperatures and allow for additional equipment and therefore associated costs for installation and operation.

For Option B, which comprises mainly air-cooling, the controlled variable will be the air cooler process outlet temperature, which will be controlled by fans operated via a variable speed drive to reduce load to maintain a process temperature set point, therefore having a more controllable operation and ensuring a more efficient operation. This option would therefore require a lower engineering effort compared to the other options under consideration.

Option C consists of open loop water cooling, so the pumps will maintain a constant flow resulting in a colder cooling water return temperature with a lower duty; the engineering effort associated with this option is therefore expected to be relatively lower than some of the other options under consideration.

All of the hybrid options (Options D1 – D3) are expected to have a mixture of issues faced by air cooled and water-cooled systems depending on the proportion of the component (wet/ dry) associated with each hybrid option. Specifically, for Options D2i and D2ii, the air-cooled option will be able to control the process temperature whereas the water-cooled option will require constant cooling water flow and therefore have a variable return temperature.

The water-cooled options will not see as large a parasitic load compared to the air-cooled option at turn down because the cooling water is a fixed flow. However, water cooled systems also have the waste generated from the solid build-up within the blowdown, which will require disposal, likely to be off-site.

Air coolers are generally considered to be noisier than water cooled options mainly due to the quantity of motor driven fans required. However, environmental assessment and achieving acceptable noise levels at the closest sensitive receptors will stipulate the maximum site noise limit allowed, therefore this is not considered to be a differentiator for any options.

In case of water-cooled options, if the leaked CO_2 finds its way into the cooling water loop it could form carbonic acid leading to corrosion of pipes. On the other in the air-cooled options, any leaked CO_2 will be vented off to the atmosphere and therefore unlikely to affect the pipes.

4.3.7 Environmental Impact

The main environmental impact associated with the available cooling options is the requirements of water abstraction for water cooling in a water constrained area. Air cooling was used for GT3 cooling back in 2009 due to concerns over water availability and this issue is still relevant now. The water usage associated with the available Options is show in Table 4.7.

Table 4.7: Indicative Water Usage Associated with the Available Cooling Options

Option	Water Usage (m^3/hr)
Option B	-58.8
Option C	879.2
Option D1	26.2
Option D2i	70.2
Option D2ii	-58.8
Option D3	761.2

It can be seen that Options C and D3 require the largest amounts of water, with Options B and D2ii requiring the least.

In addition to water usage, discharge of cooling water into the Humber Estuary SPA, SAC and Ramsar site would also result in potential environmental impacts. As such, it is consider that the water cooled options fair badly environmentally.

4.4 Option Ranking

The options have been compared in Table 4.8 using a ranking scheme whereby the lowest rank (1) is the worst, and the highest rank (7) represents the best. The rank for each of the parameters considered in the assessment has then been combined to obtain an overall rank of each option.

Table 4.8: Comparison Ranking for Cooling Options Assessed

Parameter	Ranking of Options						
	Option A	Option B	Option C	Option D1	Option D2i	Option D2ii	Option D3

Meet operating requirements	1	7	2	6	5	3	4
Land availability	-	2	7	4	4	5	6
Constructability	-	7	6	5	5	5	5
Capital and operational expenditure	-	7	3	5	4	3	6
Energy Efficiency	-	5	5	5	7	6	2
Environmental impact		7	3	6	5	7	4
Total	1	35	26	31	30	29	27
Overall Ranking	**1**	**7**	**2**	**6**	**5**	**4**	**3**

Notes: (1) Option A does not meet the operating criteria (see Section 4.3.1) and was therefore not assessed for any of the other assessment parameters, and is therefore ranked as the worst option.

(2) Where the options are assessed to represent the same/ similar benefits and/ or costs, they have been ranked the same.

Table 4.8 shows that Option B (air cooling) presents the most beneficial and cost-effective option for coolingthe PCC plants.

5. Conclusion

Whilst both air- and water-cooling systems are widely used across industries, based on the review of various operating parameters, energy efficiency and environmental effects, BAT for cooling for the PCC plants at the Installation is considered to be air-cooling (Option B).

It is recognised that some specialist equipment associated with the PCC plants (e.g. CO_2 compressors) will require a detailed study by the chosen suppliers to determine the final optimal cooling system. Therefore, closed loop water cooled systems and direct air cooling will both remain viable alternatives, pending the selection of equipment suppliers in the detailed design phase.

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