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Post-combustion capture on natural gas combined cycle plants: A technical and economical evaluation of retrofit, new build, and the application of exhaust gas recycle

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Abstract

If legislation proposing a reduction in CO_2 production from fossil-fired power plants is enacted, it is conceivable that natural gas combined cycle (NGCC) plants may be required to implement carbon capture. Therefore, as the power industry plans their future generation portfolios, there is growing interest in the feasibility and costs associated with installing large-scale carbon capture to NGCC plants. The Electric Power Research Institute (EPRI) has recently completed an assessment on the technical feasibility, performance, and cost of applying current carbon dioxide (CO_2) post-combustion capture (PCC) technologies at a typical commercial-scale NGCC power station. The study also considered the potential of exhaust gas recycle (EGR) as a novel technology for improving future NGCC capture economics.

Keywords: Post Combustion Capture (PCC); Natural Gas Combined Cycle (NGCC); Exhaust Gas Recycle (EGR); Retrofit; Carbon Capture and Storage (CCS).

1. Introduction

With coal-fired power plants producing roughly double the CO_2 of gas-fired units, the application of carbon capture and storage (CCS) technologies to date have largely centered on coal-fired assets. In the longer term, however, CO_2 reductions from natural gas-fired plants could potentially be required as well. PCC using advanced amine solvents is one technology being pursued for larger-scale, near-term power

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plant CO_2 capture. EPRI has evaluated the technical and economic applicability of both a "new-build" NGCC plant designed and built for PCC as well as PCC retrofitted on an existing NGCC plant.

The design for the full-scale, 90% carbon capture system was based on the current commercial offering of technology developed by Aker Clean Carbon (ACC) of Norway with an advanced amine solvent. ACC provided costing for their overall advanced capture process assessment and integration. Engineering consultants Norsk Energi assisted in the steam cycle analysis and optimization.

2. Objective

The objective of this study is to evaluate the performance and cost impact of applying PCC to a NGCC plant. The report initially focuses on retrofitting PCC to a reference 556.5-megawatt electric (MWe) net NGCC plant. This baseline NGCC plant had no prior considerations for CO_2 capture in its original design.

The report then considers a new-build NGCC plant designed for capture both with and without exhaust gas recycle (EGR). EGR is currently being researched and tested by several major combustion turbine (CT) suppliers including GE[1] and Alstom[2].

Several key issues related to EGR are:

- This study assumes this plant to be the nth-of-a-kind plant (meaning the costs after the technology has matured and multiple installations have occurred) implementing EGR technology, and therefore a recycle rate of 45% of the flue gas from the CT is considered achievable
- Modification of the combustion chamber will likely be required to obtain this target recycle level. A preliminary estimate for appropriate turbine modifications has been included.

All four NGCC cases are considered at the same Kenosha, Wisconsin, USA site reference location. This is in line with other published EPRI capture studies for integrated gasification combined cycles (IGCC)[3], oxy-combustion[4], and pulverized coal with PCC[5].

3. Plant Equipment and Layout

Key components associated with the ACC design are presented in Table 1.

Table 1. Comparison of PCC Plant Key Components

NGCC + PCC Retrofit (No Considerations for Capture)	**New-Build NGCC + Capture (Designed for Capture)**	**New-Build NGCC + Capture + EGR (Designed For Capture)**
2 Absorber trains	2 Absorber trains	1 Absorber train*
1 Desorber train	1 Desorber train	1 Desorber train
4 Reboilers per desorber	4 Reboilers per desorber	4 Reboilers per desorber
2 Compression trains	2 Compression trains	2 Compression trains

* Note: When EGR is applied to the new-build designed for capture case, 1 less absorber is envisaged.

Figure 1 illustrates the estimated plot requirements for retrofitting the PCC equipment to the existing NGCC plant. Approximately 3.7 acres (15000 m^2) are required to site the new PCC equipment, including the additional cooling towers required.

Figure 2 illustrates the estimated change in plot requirements for the PCC equipment when EGR is included in a new-build design. The left-hand image in the figure shows the plant with EGR included (notice the single absorption train on the left versus the two trains on the right). An approximate 0.5 acre (2000 m^2) reduction in PCC footprint is estimated with the EGR case.

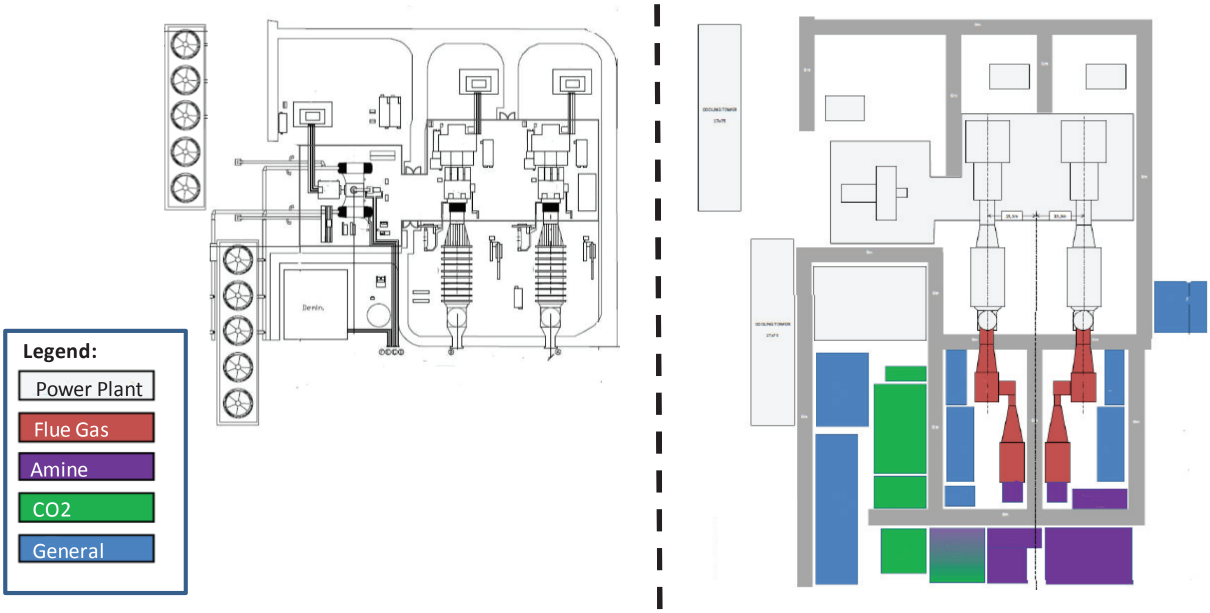

Figure 1. Schematic Plot Plans for NGCC Power Plant before and after ACC PCC Retrofit (No EGR)

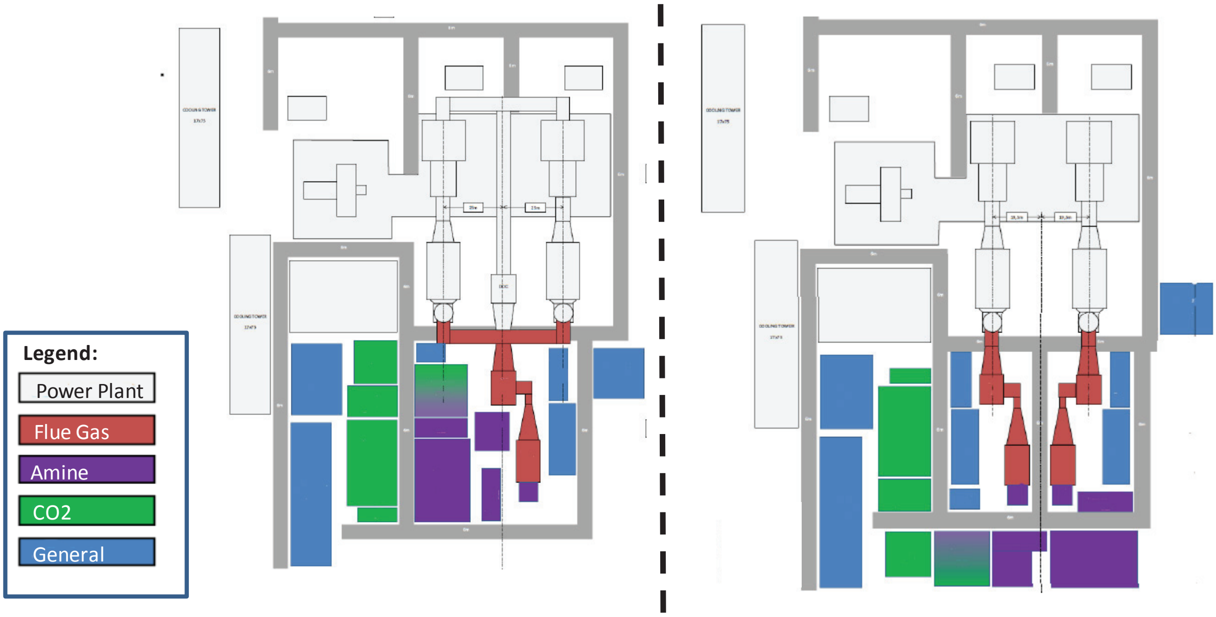

Figure 2. Schematic Plot Plans for New-Build NGCC Power Plant with ACC PCC (with and without EGR)

4. Integration Aspects Considered

Figures 3 and 4 illustrate the integration between the PCC plant and the existing NGCC plant. The integration between the PCC plant and the NGCC plant is described in detail within the main report and appendices.

The following points are noted:

- For all cases, the design allows operation with or without CO_2 capture and allows 90% capture to be achieved with minimal intrusion to the plant steam turbine
- Two F-class CTs are proposed as the base power plant (e.g., GE 7FA.05 or Siemens SGT6-5000F4)
- Due to the risk of over/under pressurizing the heat recovery steam generator (HRSG) section and the CTs in case of upset conditions, an "open stack design" with a plenum is proposed. This minimizes the effects on the HRSG during normal CO_2 capture, but even more importantly reduces any negative transient or static impact (pressure build-up) on the boiler in the case of an unplanned shut down or other transient operating mode of the capture plant.
- For all cases, the PCC plant obtains steam for solvent regeneration via the intermediate-pressure (IP)/low-pressure (LP) crossover of the existing steam turbine
- The EGR case is implemented to increase the CO_2 concentration in the NGCC plant exhaust from 3.9% vol CO_2 to 7.3% vol CO_2. Such a difference in partial pressure of CO_2 in the flue gas will have a beneficial effect on the energy requirements of the capture process and in turn save capital and operational cost of CO_2 capture equipment. The resulting drop in oxygen concentration may also reduce amine losses due to carryover and oxidation[6].

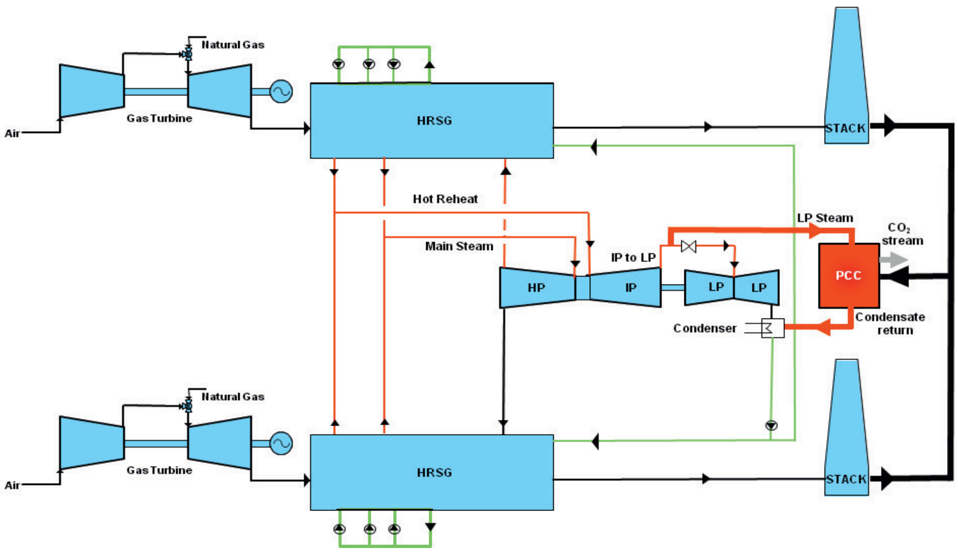

Figure 3. Schematic of NGCC Plant with CO_2 Capture

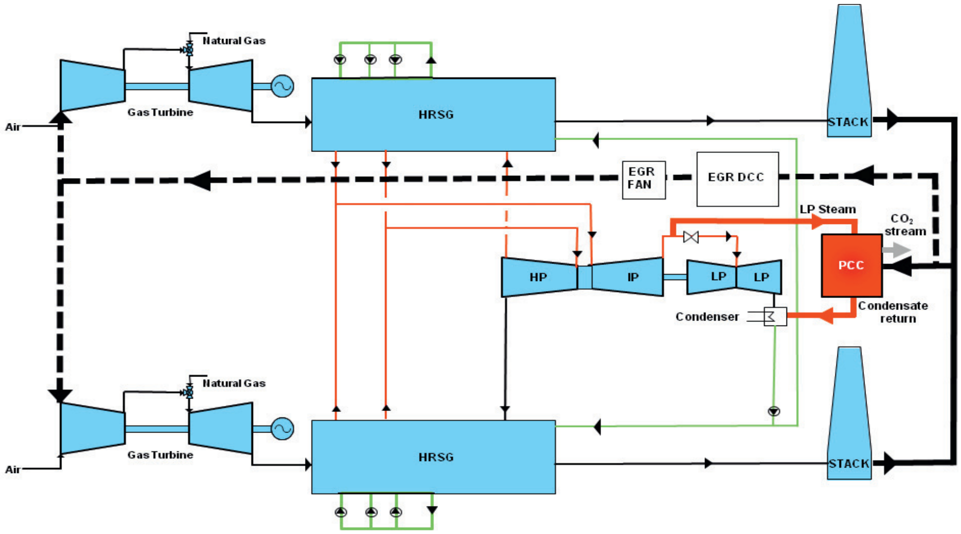

Fig 4.Schematic of NGCC Plant with EGR and CO_2 Capture

5. Performance Assessment.

Table 2. Summary Performance Results

	CASE 1 NGCC Plant (Reference)	CASE 2 NGCC PLANT (Retrofitted with PCC)	CASE 3 NEW-BUILD NGCC PLANT (Designed with PCC + EGR)	CASE 4 NEW-BUILD NGCC PLANT (Designed with PCC)
Gas Turbine Output (MWe)	368.8	368.8	368.8	368.8
Steam Turbine Output (MWe)	197.3	163.5	163.5	163.5
Gross Power Output (MWe)	566	532.3	532.3	532.3
Aux Load (MWe)	9.5	45.1	38.6	45.1
Net Power Output (MWe)	556.5	487.2	493.7	487.2
Net Plant Heat Rate (Btu/kWh HHV)	6625	7560	7470	7560
Net Plant Efficiency (% LHV)	56.9%	49.8%	50.5%	49.8%
Efficiency Reduction (% Points LHV)		7.1%	6.4%	7.1%
Net Plant Efficiency (% HHV)	51.5%	45.1%	45.7%	45.1%
Efficiency Reduction (% Points HHV)	-	6.4%	5.8%	6.4%

The summary performance results of the ACC process are shown in Table 2. The first column shows the performance results of the NGCC plant without capture (CASE 1). The second column shows the same baseline NGCC plant retrofitted with capture using an ACC process with a solvent selected for a natural gas combustion flue stream (CASE 2). On a higher heating value (HHV) basis, the retrofit CASE 2 can be seen to have a calculated efficiency penalty of 6.4% points compared to CASE 1. The 556.5 MWe net output of CASE 2 drops 12.5% to 487.2 MWe as a direct result of the capture plant addition. The solvent heat of regeneration for all the NGCC CASES is 1300 Btu/lb (3024 kJ/kg) CO_2. CASE 3 in Table 2 shows a new-build plant scenario for the same ACC solvent process and with EGR included.

Compared to CASE 2 the estimated improvements in plant performance for new-build CASE 3 are:

- Increase in plant efficiency of the capture plant by 0.6 percentage point to 45.7% HHV
- Increase in net output by 6.5 MWe to 493.7 MWe
- Decreases in power lost from capture by 1.2 percentage points to 11.3%.

CASE 4 in Table 2 presents the new-build NGCC plant with capture but without the EGR. The performance is assumed identical to the retrofit scenario CASE 2; however cost savings are identified for the new-build scenario, which are highlighted below.

6. Economics Assessment

The economic results of the ACC process are illustrated in Figures 5, 6, and 7 and summarized below. All capital costs estimates are to +/- 30% accuracy and represented by the graded error bars.

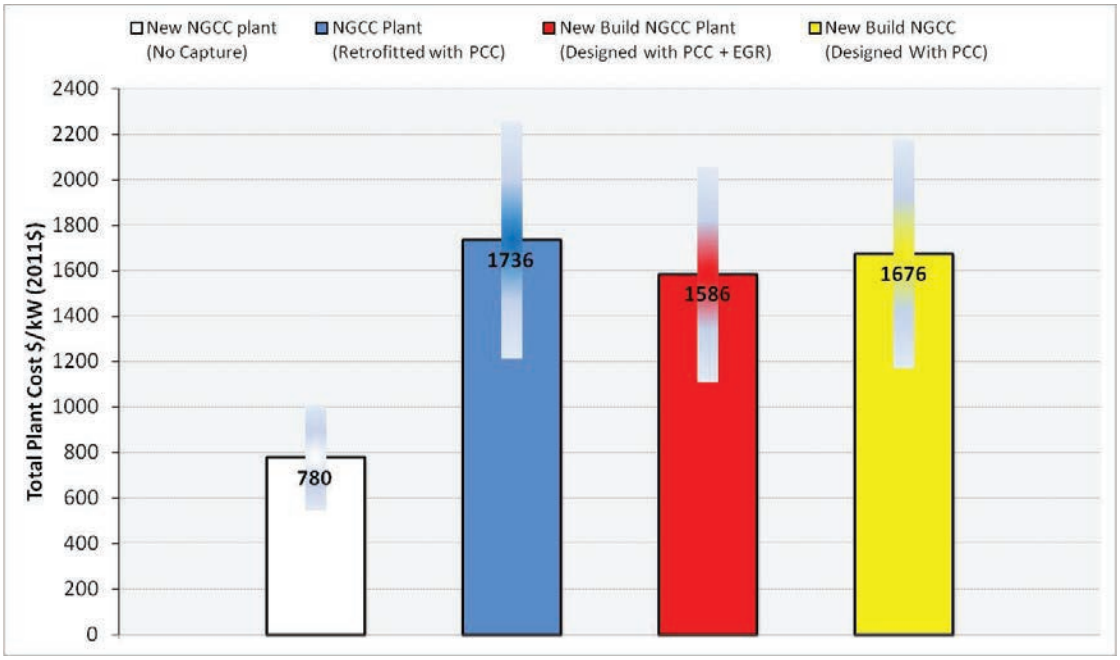

Figure 5. Total Plant Cost with and without CO_2 Capture
(Note: Key economic assumptions are listed in Appendix A)

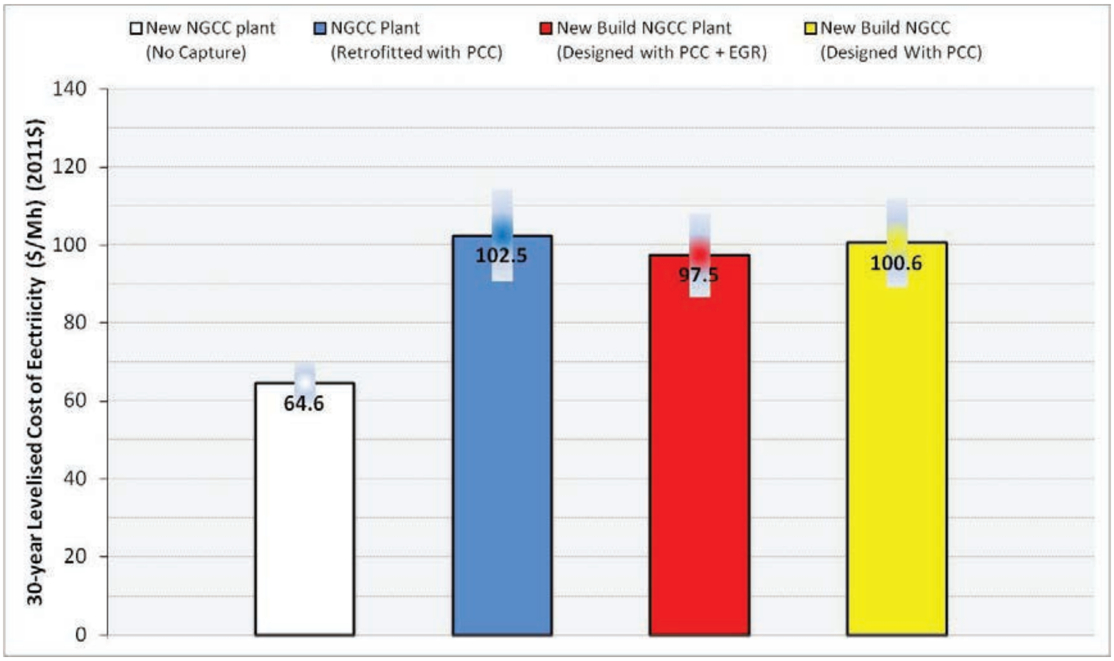

Figure 6. LCOE with and without CO_2 Capture
(Note: Key economics assumptions are listed in Appendix A)

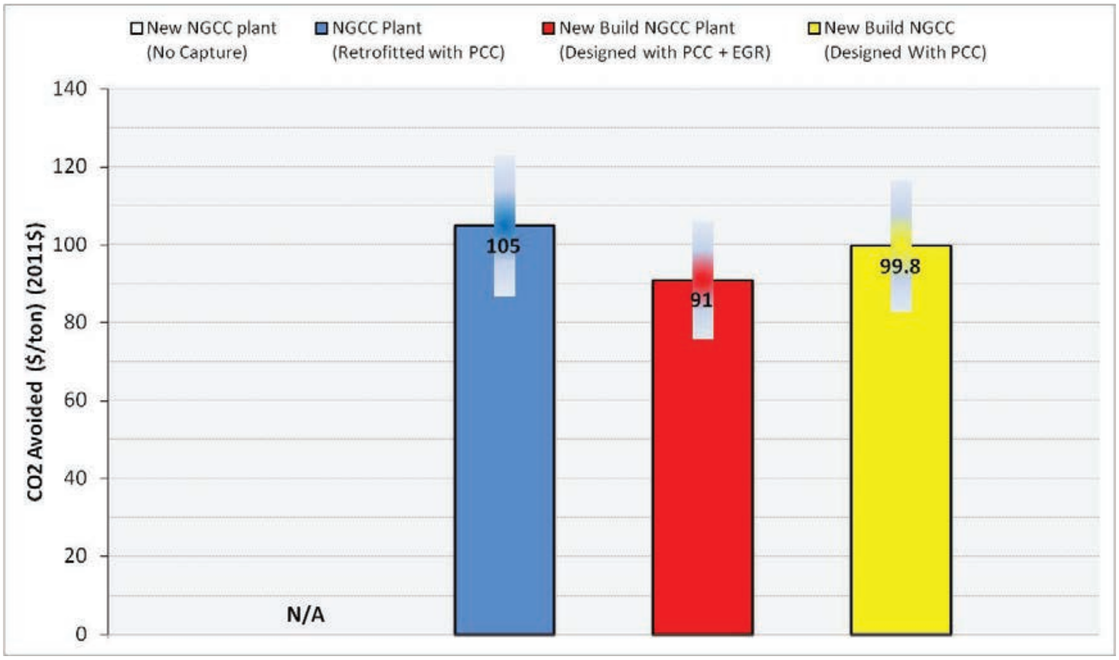

Figure 7. Cost of CO_2 Avoided
(Note: Key economic assumptions are listed in Appendix A)

6.1. Total Plant Cost (TPC) with and without Capture

Note: the various inputs included in the TPC presented are outlined in Appendix A. Figure 5 presents the derived TPC ($/kWe), for the NGCC plant cases with and without capture. Comparing each case with the baseline NGCC without capture (CASE 1), the graph shows:

- 123% increase in TPC associated with retrofitting the ACC capture technology (CASE 2)
- 103% increase in TPC associated with the new-build NGCC designed with PCC and EGR (CASE 3)
- 115% increase in TPC associated with the new-build NGCC designed with PCC (CASE 4)

6.2. Levelized Cost of Electricity (LCOE) with and without Capture

Figure 6 presents the derived LCOE ($/MWh) for the NGCC with and without capture. Comparing each case with the baseline NGCC plant without capture (CASE 1), the graph shows:

- 59% increase in LCOE associated with retrofitting the ACC capture technology (CASE 2)
- 51% increase in LCOE associated with the new-build NGCC designed with PCC and EGR (CASE 3)
- 56% increase in LCOE associated with the new-build NGCC designed with PCC (CASE 4)

6.3. Cost of CO_2 Avoided

Figure 7 presents the derived cost of CO_2 avoided ($/ton) for ACC's current commercial offering against the baseline NGCC plant (CASE 1). The graph shows:

- $105/ton ($116/tonne) as the calculated avoided cost of CO_2 for the retrofit (CASE 2)
- $91/ton ($101/tonne) as the calculated avoided cost of CO_2 for the new-build NGCC plant designed with PCC and EGR (CASE 3)
- $99.8/ton ($111/tonne) as the calculated avoided cost of CO_2 for the new-build NGCC plant designed with PCC but without EGR (CASE 4)

7. Conclusions

The following conclusions can be made from the engineering and economic study:

- Retrofitting NGCC with PCC technology was more expensive than designing and building the PCC into the original NGCC plant.
- EGR lowered capital outlay, increased efficiency, and provided an incremental improvement to the LCOE for the new build NGCC with PCC Case.
- In terms of cost of avoided CO_2, the NGCC retrofit of PCC technology has a higher avoided cost when compared to designing and building the PCC into the original NGCC design
- The application of EGR illustrates potential for further reducing the cost of avoided CO_2 for the new-build plants with capture
- As with all economic studies of this type, the results were found to be sensitive to the original assumptions made (See Appendix A for the key assumptions associated with this study)
- Additional sensitivity analysis showed:
  - Adding a 20% contingency directly to the PCC equipment costs results in a 3.5% increase in the LCOE and a 10% increase in the cost of CO_2 avoided across all 3 capture cases
  - The larger the capacity factor, the smaller the increase in LCOE associated with adding capture
  - The larger the capacity factor, the lower the cost of avoided CO_2
  - An increase in the price of natural gas has more impact on the LCOE than the CO_2 avoided cost.

8. Acknowledgements

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9. References

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Appendix A.

Key economic assumptions included in this study:

• No contingency applied to PCC equipment	• 60% capacity factor applied
• Gas price used is \$7.00/MBtu (\$6.6/GJ) HHV	• All capital costs have been adjusted to 4th quarter 2011 dollars
• Costs estimate were based on a +/- 30% accuracy from pre-front-end engineering and design studies	• All Kenosha, Wisconsin based site conditions
• LCOE based on investor-owned utility revenue requirement analysis	• 11.9 % annual capital carrying charge factor applied
• The base plant for the avoided cost of CO_2 calc was the NGCC without capture (CASE 1)	• Captured CO_2 is compressed to 2205 psig (152 barg)

- Constant value of \$9.1/ton (\$10/tonne) was applied to account for transport and storage.
- The TPC used, is defined as the sum of the following: Capital cost (broken into materials and installation including labor, subcontracts, field indirect costs, no sales tax assumed) / Engineering and other Home Office Overhead, including Fee / Warranty costs / Any Contingencies applied.