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Capture-ready coal plants—Options, technologies and economics

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ABSTRACT

This paper summarizes the spectrum of options that can be employed during the initial design and construction of pulverized coal (PC), and integrated gasification and combined cycle (IGCC) plants to reduce the capital costs and energy losses associated with retrofitting for CO_2 capture at some later time in the future. It also estimates lifetime (40 year) net present value (NPV) costs of plants with differing levels of pre-investment for CO_2 capture under a wide range of CO_2 price scenarios. Three scenarios are evaluated—a baseline supercritical PC plant, a baseline IGCC plant and an IGCC plant with pre-investment for capture. This analysis evaluates each technology option under a range of CO_2 price scenarios and determines the optimum year of retrofit, if any. The results of the analysis show that a baseline PC plant is the most economical choice under low CO_2 prices, and IGCC plants are preferable at higher CO_2 prices (e.g., an initial price of about \$22/t CO_2 starting in 2015 and growing at 2%/year). Little difference is seen in the lifetime NPV costs between the IGCC plants with and without pre-investment for CO_2 capture. This paper also examines the impact of technology choice on lifetime CO_2 emissions. The difference in lifetime emissions become significant only under mid-estimate CO_2 price scenarios (roughly between \$20 and 40/t CO_2) where IGCC plants will retrofit sooner than a PC plant.

1. Introduction

Interest in the construction of coal-fired power generation has increased significantly in recent years, sparked by continually increasing demand for electricity, combined with volatile prices of other fossil fuels, including natural gas and oil, the difficulties surrounding the construction of nuclear facilities, and the current challenges of availability and pricing of alternative generation technologies, such as solar and wind. In the United States alone it is expected that overall electricity demand will increase from 3650 billion kilowatt-hours in 2002 to over 5500 billion kilowatt-hours in 2025 (United States Department of Energy, 2005). Even without considering replacing old plants, this will require over 250 GW of new generation capacity. Of this new capacity, the EIA estimates that 80 GW will be met through the construction of coal-fired plants. Worldwide, the installed capacity of coal-fired plants is expected to increase by over 40% in the next 20 years, and by 2025 it is expected to exceed 1400 GW (United States Department of Energy, 2005).

While coal-fired power plants offer significant cost and energy security advantages, they are also major sources of criteria air pollutants such as NO_X and SO_2, air toxics such as mercury, and greenhouse gas emissions, namely CO_2. With an

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expected lifespan of 40 years or more, these plants will account for a significant portion of future global rises in greenhouse gas concentrations if no actions are taken to capture and sequester the CO_2 from them. This issue is compounded by the fact that the large majority of both existing and proposed plants are expected to be prohibitively expensive to retrofit for CO_2 capture and sequestration (CCS) at a later point (MIT, 2007). This problem can be addressed if, during the initial design and construction phase, the plant is designed to be 'capture-ready', which this study defines as follows:

> *A plant can be considered 'capture-ready' if, at some point in the future it can be retrofitted for carbon capture and sequestration and still be economical to operate.*

The concept of 'capture-ready' is not a specific plant design; rather it is a spectrum of investments and design decisions that a plant owner might undertake during the design and construction of the plant. If carbon prices are high enough it is expected that any coal-fired power plant will be more economical to retrofit for CCS than to operate as is. It is also expected that if retrofitting for CCS results in an overly large output de-rating and increase in operating costs (including fuel), it would be more economical to decommission the plant and build a more efficient plant in its place.

The potential value of capture-ready power plant designs was recognized by members of the G8 nations at the 2005 Gleneagles Conference on clean energy and sustainable development. In their plan of action, released at the conclusion of the conference, the members identified that the "acceleration of the development and commercialization carbon capture and storage technology" should be pursued by "investigating the definition, costs and scope for 'capture-ready' plants and the consideration of economic incentives" (G8, 2005). Gaining a better understanding of what appropriate steps to build capture-ready plants is a priority to members of the G8 because new power plant installations will be around for decades to come. In addition, plants that are not designed to be 'capture-ready' could prove to be prohibitively expensive to retrofit in the future, resulting in either delayed reductions in CO_2 emissions, or stranded generation assets.

From an owner perspective, the technology choice is driven primarily by economics. The additional costs and actions required to build a capture-ready facility and the subsequent retrofit costs are expected to be significant barriers to its adoption. Added to these costs are the uncertainties of future carbon price levels.

The first section of this paper defines the technologies and options for capture-ready plants by exploring the capital and technical requirements for capture-ready for both traditional pulverized coal (PC) and integrated gasification and combined cycle (IGCC) power plants. The second part of this paper develops a methodology to determine under which carbon price scenarios it is economically optimal to build a capture-ready plant. It applies the methodology to a number of technology options, and determines what the impacts of the technology selections are on lifetime net present value (NPV) costs and CO_2 emissions of each case. It also evaluates the concept of CO_2 "lock-in," which occurs when a newly built plant is so prohibitively expensive to retrofit for CO_2 capture that it will never be retrofitted.

2. Choices for capture-ready plants

Some of the issues that face owners considering retrofitting their plants for carbon capture and sequestration include:

- Capital costs and the associated financing of the capture equipment.
- Large reduction in the net electrical output of the plant.
- Increased operation and maintenance costs.
- Increased total and variable cost of electricity (COE).
- Location and access to a suitable sequestration site.
- Timing and length of the downtime required for the retrofit.
- Physical space for new equipment.

The issues surrounding the retrofitting of these plants are significant and their magnitudes will vary from plant to plant. Due to this heterogeneity with existing power plants, the suitability for retrofit for each plant would have to be evaluated individually.

2.1. *Pulverized coal*

While no major technical hurdles exist for retrofitting PC plants with post-combustion capture, the expected de-rating, capital requirements and increase in operation and maintenance costs pose significant challenges to owners and policymakers if and when actions are taken to reduce CO_2 emissions from these facilities. Some of the issues that are specific to retrofitting PC plants with post-combustion capture include:

- A 20–30% reduction in the electrical output of the power plant due to the diversion of significant amounts of low-pressure steam to the re-boilers of the monoethanolamine (MEA) CO_2 recovery system and the need for electric power to drive the CO_2 compressors (Nsakala et al., 2001).
- The low-pressure stage of the steam turbine may need to be rebuilt in order to be able to handle the lower low-pressure steam availability, unless additional steam is provided from an alternative source.
- The stringent sulfur level limits of the MEA solvent may require an upgrade of the existing flue gas desulfurization equipment.
- Additional space requirements for the CO_2 recovery and compression system, which may cause difficulties for existing plants that do not have space readily available.

Less operational experience exists with oxyfired PC plants, but studies indicate that the oxyfired technology may have capital cost and efficiency advantages over post-combustion capture (MIT, 2007). Some of the issues specific to the retrofitting of PC plants with oxyfired combustion capture include:

- Significant changes are required to the air handling system as a flue gas recycling system will be required in order to keep the temperatures and heat transfer properties of the combustion gasses within the operating range of the boiler.

- Boiler air leakage can dilute the flue gas to unacceptable levels, and the boiler may require modifications to minimize the levels of air infiltration.
- The power requirements of the air separation unit, which consume on the order of 20% of the generator output (Nsakala et al., 2001).
- Additional space requirements for the air separation unit, flue gas non-condensables removal system, and the CO_2 compression and drying equipment.

The capture-ready options for PC plants are relatively limited, but some steps can be taken to reduce impacts of a retrofit on the capital requirements and derating of the plant. These include:

- The pre-investment in a high-efficiency supercritical or ultra-supercritical boiler, which would reduce the amount of CO_2 being produced by the plant per unit output and correspondingly reduce the capital costs and energy requirements of capture equipment, and the derating of the plant.
- Leaving extra space in appropriate places for the capture equipment.
- Ensuring that the plant site is located close to an appropriate sequestration site, and the required easements for a CO_2 pipeline system is available.

2.2. *Integrated gasification/combined cycle*

IGCC technology offers advantages over PC plants for CO_2 capture as the CO_2 can be separated at higher partial pressures, reducing the amount of capital required and lessening the energy penalty for capture. Less operational experience exists with IGCC plants, however, and they are more complicated to operate and construct than a traditional PC plant. Some of the issues that are specific to retrofitting IGCC plants for CO_2 capture include:

- The water-gas shift reaction of the syngas and CO_2 removal reduces the heating value of the syngas by approximately 15%, which would cause a derating of the combustion turbine (EPRI, 2003).
- The convective and radiative gas coolers may no longer be required, as a water quench system can cool the syngas and generate the steam for the water-gas shift reaction.
- The acid gas removal system would require an additional unit to remove CO_2 in addition to H_2S. The methyldiethanolamine (MDEA) system (if present) may need to be removed and replaced with two-stage Selexol-type acid gas removal system.
- In order to operate on hydrogen gas, the turbine combustors may need replacement and the turbine blades may require modification.
- Compressed air for the air separation unit may no longer be available from the turbine, necessitating the addition of a parallel air compressor.
- Re-arrangement of existing equipment may be required to accommodate the addition of the water-gas shift reactors, a second acid gas removal unit and CO_2 compression and drying equipment.

The capture-ready options for IGCC plants have been more widely explored than for PC plants, and several opportunities exist to reduce the de-rating and capital costs of a retrofit. These options include:

- The pre-investment in over-sizing the gasifier and air separation unit, to ensure that sufficient hydrogen can be produced to maintain full loading of the turbine, reducing the derating of the plant.
- The selection of a high-pressure gasifier design, which would reduce the energy requirements of the CO_2 compression equipment.
- The selection of a water quench gas cooler, which eliminates the capital in gas coolers that may be stranded after a retrofit (Holt, 2005).
- Leaving extra space for the addition of the water-gas shift reactors, second acid gas removal stage and CO_2 compression and drying equipment.
- Ensuring that the plant site is located close to an appropriate sequestration site, and the required easements for a CO_2 pipeline system is available.

3. Economics of capture-ready plants

The construction of capture-ready plants will only be economic with regulations or taxes in place that effectively create a CO_2 price. Sekar et al., 2005 performed an NPV analysis to determine the CO_2 price levels and growth rates that would be required in order to justify building a baseline IGCC plant, which is more expensive to build and operate than a PC plant, but less expensive to retrofit for CO_2 capture. A range of future CO_2 prices and their growth were overlaid on this analysis.

This paper has expanded upon the economic analysis performed by Sekar et al., 2005 in three major ways. First, the costs and de-rating of retrofitting a plant for CO_2 capture, as well as the performance and operating costs of the plant after retrofit, have been updated.[1] This was done for both the PC and IGCC technologies, and the following data sources were used in developing the costs:

- The cost of the baseline (and makeup) PC and IGCC plants were taken from the MIT Coal Study (MIT, 2007).
- The costs of pre-investment and retrofitting of the IGCC plants were taken from the EPRI Phased Construction Report (EPRI, 2003).
- The costs of pre-investment and retrofitting the PC plant was developed in Capture Ready Power Plants—Options, Technologies and Economics (Bohm, 2006).

Second, the analysis adds a second IGCC case that includes additional investments in capture-ready technologies. These pre-investments reduce both the capital costs of retrofitting,

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[1] This analysis was done before the recent large increase in commodity and other costs associated with building new power plants. While this will change the absolute values of the costs presented here, the relative costs of the different cases are still valid and, therefore, the paper's conclusions will be unchanged.

and the expected de-rating of the plant after the retrofit is complete. The pre-investments considered include over-sizing the gasifier and the air separation unit. The final expansion of this analysis is the evaluation of the lifetime emissions of a plant, and provides guidance to policymakers on whether or not the issue of CO_2 'lock-in' is a concern for coal-fired power plants that will be built in the near future. This is of particular concern for policymakers as the power plants being built now are expected to be operating for 40 years or more. Without CO_2 controls, a 500 MW baseload coal-fired power plant would emit over 100 Mt of CO_2 during its 40 year lifetime.

The model uses standard net present value (NPV) methodology to calculate costs and the optimal year of retrofit for each case, under a range of carbon price scenarios. The NPV calculations included the costs of building and retrofitting the plant, fuel and operation and maintenance (O&M) costs, as well as any carbon emissions costs. The cost of a makeup plant equivalent in size to the level of de-rating caused by the CCS retrofit is also included in the analysis. This is done to keep the electricity output constant in all cases, thereby eliminating electricity price as a variable in the economic analysis. Each case assumed that the plant would begin to operate in 2010 and the carbon price would take effect in 2015.

The optimal year of retrofit (if any) was determined for each case under each carbon price scenario by determining which year of retrofit gave the lowest NPV costs. The three technology cases evaluated in this study are described below.

3.1. *Baseline PC*

The technology selected for the baseline PC plant in this study is supercritical PC with an efficiency of 38.5% (HHV). This technology was selected because it is the base case that was used in the MIT Coal Study (MIT, 2007), and appears to be the most likely of the advanced PC technologies to be constructed in the near term in the US. The plant is assumed to have advanced pollution control, with both selective catalytic reduction (SCR) for NO_X control and flue-gas desulfurization (FGD) for SO_2 control.

After retrofitting for CO_2 capture, the plant is expected to have an output de-rating of 30.4%, reducing output by 152 MW, which is significantly higher than either of the two IGCC cases described later in this section. This de-rating was calculated by assuming that the CO_2 compression and pumping energy requirements would be the same as in a greenfield plant, but the energy requirements associated with producing steam for the CO_2 capture process would be 50% higher (Bohm, 2006). This reflects the difficulty of heat integration between the power plant and the capture process in a retrofit versus a Greenfield plant. The plant before retrofit is estimated to cost $665 million, and the retrofit is estimated to cost $277 million. The additional cost of adding a 152 MW makeup plant (assumed to be a greenfield supercritical PC with MEA capture) is estimated to cost $325 million.

3.2. *Baseline IGCC*

The baseline IGCC plant was assumed to be a high pressure (6.20 MPa) GE/Texaco gasifier with radiant and water quench gas cooling, an F-class combustion turbine, and a Selexol acid gas removal system. This plant has an efficiency of 38.4% (HHV) and is the same design as the baseline no-capture IGCC plant in the MIT Coal Study (MIT, 2007). The plant is expected to have an output de-rating of 18.8%, reducing the output to 406 MW, which is significantly lower than the de-rating of the PC plant, but higher than the IGCC plant with pre-investment.

For this evaluation, a base case IGCC was developed in consulting both the EPRI report (EPRI, 2003), and the MIT coal study (MIT, 2007). The plant is optimized for no capture, with the size of the gasifier and air separation unit matching the heat input requirements of the combustion turbine. There were no accommodations made to make up for the reduction in heat rate input to the combustion turbine after retrofit. The capital costs for this case were taken from values from the MIT coal study (MIT, 2007).

The plant before retrofit is estimated to cost $715 million. To estimate the costs of the retrofit, it was assumed that the radiant gas cooler would no longer be necessary, and would be scrapped during the retrofit. This adds $61 million to the cost of the retrofit over a greenfield capture plant, which would have specified only a water quench cooling system (Holt, 2005). In addition, the mismatch between the gasifier/ASU and combustion turbine results in a greater de-rating than the greenfield plant (Sekar et al., 2005). The total cost of the retrofit is estimated to be $131 million. The additional cost of adding a 94 MW makeup plant (assumed to be a greenfield IGCC plant with capture) is estimated to cost $178 million.

3.3. *IGCC with pre-investment*

The IGCC with pre-investment design that was selected for this study is similar in design to baseline IGCC plant, except the air separation unit and gasifier are oversized by approximately 10% during the initial construction phase. Before the retrofit, the efficiency and marginal operating costs are expected to be the same as the baseline IGCC plant. The estimate of output de-rating was taken from the EPRI Phased Construction Report (EPRI, 2003). Once the retrofit is complete, the pre-investment reduces the output de-rating of the plant to 14% as compared to 18% for the baseline IGCC.

The plant before retrofit is estimated to cost $745 million, with the additional $30 million capital required over the baseline IGCC plant directed towards the pre-investment actions. The total cost of the retrofit is estimated to be $133 million. The additional cost of adding a 70 MW makeup plant (assumed to be a greenfield IGCC plant with capture) is estimated to cost $132 million.

The cost inputs and economic parameters used in this analysis are summarized in Tables 1 and 2, respectively.

4. Results and discussion

4.1. *Optimal technology choice for a given carbon price scenario*

Under the scenario where no carbon price is expected during the life of the plant, the baseline PC case is the preferred technology option, followed by the baseline IGCC plant, and

Table 1 – Base case cash flow model: capital and operational costs for 500 MW PC, baseline IGCC and IGCC with pre-investment

Case	Baseline PC	Baseline IGCC	IGCC with pre-investment (capture-ready)
Technology	Supercritical PC	IGCC with radiant and quench gas cooling	IGCC with radiant and quench gas cooling
Before retrofit			
Investment (M$)	665	715	745
O&M cost (M$/year)	26.3	31.5	31.5
Fuel cost (M$/year)	46.6	46.7	46.7
CO_2 released (Mt/year)	2.9	2.9	2.9
After retrofit[a]			
Retrofit investment (M$)	602	309	265
O&M cost (M$/year)	56.1	36.8	36.8
Fuel cost (M$/year)	65.2	57.5	57.5
CO_2 released (Mt/year)	0.41	0.36	0.36
CO_2 captured (Mt)/year	3.7	3.2	3.2

[a] Includes incremental costs of building and operating a makeup-power plant to maintain output constant at 500 MW.

then the IGCC with pre-investment plant. This was expected because without an economic incentive (the carbon price) there would be no economic reason to make additional investments in a plant that had lower retrofit costs, because there are no incentives for the retrofit to occur.

This situation changes once a carbon price is implemented. Fig. 1 illustrates the impact of carbon prices introduced in 2015 on NPV costs for a plant built in 2010. The carbon prices have a growth rate of 2% per year (e.g., an initial carbon price of \$25/t CO_2 in 2015 would rise to \$34/t CO_2 in 2030, all in constant 2005\$). Under this scenario, the baseline PC case is the most economic choice for the owner unless the initial carbon price is expected to exceed \$22/t CO_2. The difference is relatively small, however, with the lifetime NPV cost difference between baseline IGCC plant and the baseline PC never exceeding \$91 million or 7% of the total NPV cost. For an IGCC with pre-investment plant, the differences are slightly higher, but still relatively small compared to the lifetime NPV costs of the plant. The lifetime NPV cost of the IGCC with pre-investment plant never exceeds \$117 million, or 10% of the total.

In the event of a high (exceeding \$22/t CO_2) initial carbon price level, the advantages of both the baseline and IGCC with pre-investment plant becomes significant. At an initial CO_2 price of \$50/t CO_2, the lifetime NPV costs of the baseline IGCC is \$280 million (16%) lower than the baseline PC. The IGCC with pre-investment has a slightly greater savings in NPV costs of \$285 million.

Table 2 – Economic parameters used in analysis

Economic parameter	Value
Discount rate (constant 2005\$)	6.0%
Inflation rate	2.5%
Year of plant startup	2010
Plant lifetime	40 Years
Capacity factor	80%
Fuel cost (high heating value basis)	\$1.42/GJ
Net output	500 MW
Tax rate	40%
Depreciation rate (annual on remaining capital)	30%
Insurance and property tax rate	1.78%
CO_2 transportation and sequestration cost	\$5/t CO_2

Fig. 2 illustrates the impact of the higher price growth rate on the lifetime NPV costs of the cases that were evaluated in this study. For the case of a 5% growth rate, the initial carbon price required for an IGCC plant (baseline or capture-ready) to be the economically preferred option drops significantly, to \$13/t CO_2. As with the 2% growth rate case, the IGCC plant with pre-investment does not have significant lifetime NPV savings (or costs) when compared with the baseline IGCC plant.

By calculating the NPV costs for each technology under a wide range of initial carbon prices and growth rates, this study has developed a matrix that illustrates which technology choice is optimal. Fig. 3 illustrates the results of this analysis. The solid lines divide the areas on the matrix in which each technology choice is optimal. On the left-hand side a baseline PC plant is the optimal choice. On the right-hand side, a pre-investment IGCC plant is the optimal choice. Between the two, at the top of the chart, a baseline IGCC plant is the optimal technology choice. Which technology choice is optimal depends on the owner's expectations of future carbon price levels and their rates of increase.

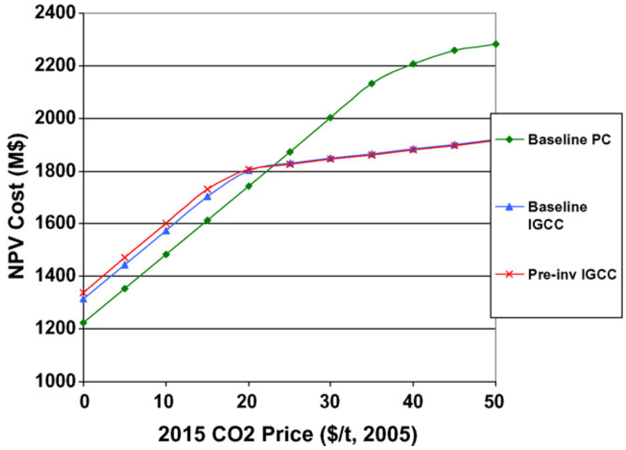

Fig. 1 – Forty-year NPV cost of plant as a function of the initial CO_2 price for a 2% annual CO_2 price growth rate.

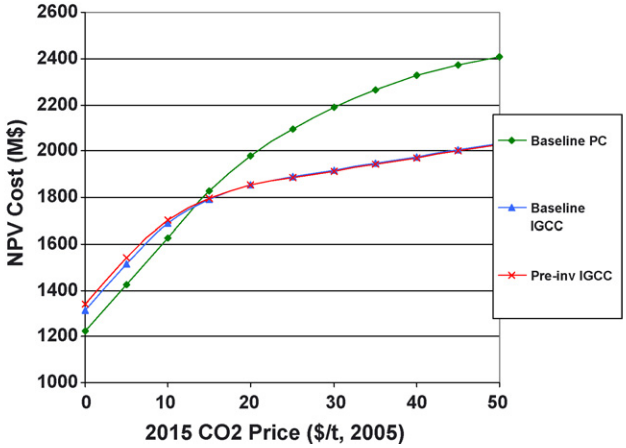

Fig. 2 – Forty-year NPV cost of plant as a function of the initial CO_2 price for a 5% annual CO_2 price growth rate.

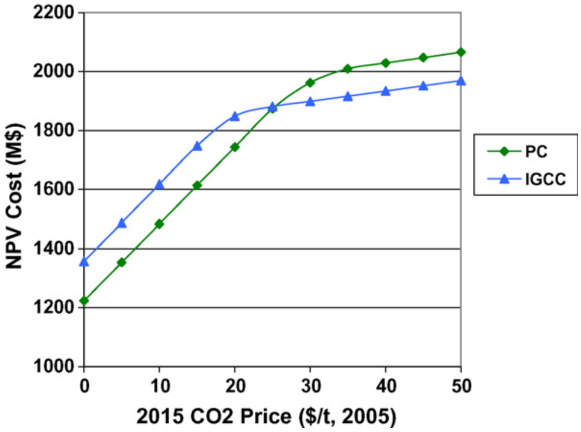

Fig. 4 – Forty-year NPV cost of plant as a function of the initial CO_2 price for a 2% annual CO_2 price growth rate and using the alternate cash flow model (see Table 3).

Table 3 – Alternate cash flow model: capital and operational costs for 500 MW PC and baseline IGCC

Case	Baseline PC	Baseline IGCC
Technology	Supercritical PC	IGCC with radiant and quench gas cooling
Before retrofit		
Investment (M$)	665	765
O&M cost (M$/year)	26.3	31.5
Fuel cost (M$/year)	46.6	46.7
CO_2 released (Mt/year)	2.9	2.9
After retrofit[a]		
Retrofit investment (M$)	409	320
O&M cost (M$/year)	51.5	36.8
Fuel cost (M$/year)	60.3	57.5
CO_2 released (Mt/year)	0.38	0.36
CO_2 captured (Mt/year)	3.4	3.2

[a] Includes incremental costs of building and operating a makeup-power plant to maintain output constant at 500 MW.

The above analysis relied on the cash flow models detailed in Table 1. To test the sensitivity of these results, the analysis was redone using cash flows from Table 3. The new cash flow model assumes a 15% capital cost premium of IGCC compared to PC (versus 7% in the base case). It also significantly cuts the cost of the PC retrofits. As seen in Fig. 4, the NPV cost advantage of PC over IGCC widens before the crossover point and the NPV cost advantage of IGCC over PC narrows after the crossover point. However, the crossover point changes only modestly for the two cash flows (from \$22/t CO_2 to \$26/t CO_2). This is because the critical parameter in determining the crossover point is the cost of retrofitting the IGCC plant, which remains the same for both cash flows.

The above analyses are all deterministic. That is, given a future carbon price trajectory, the optimum technology is determined. However, as seen in Fig. 1, the magnitudes of the differences in NPV costs are significant on differing sides of the crossover point. To take this into account, we can do a probabilistic analysis. This is shown in Table 4, where probabilities are assigned to different initial CO_2 prices for the 2% annual growth rate scenario. Using the base case cash flow model, IGCC technology is preferred, while PC technology is preferred when using the alternate cash flow model. This illustrates the sensitivity of the results to both the cash flow models and the carbon price assumptions.

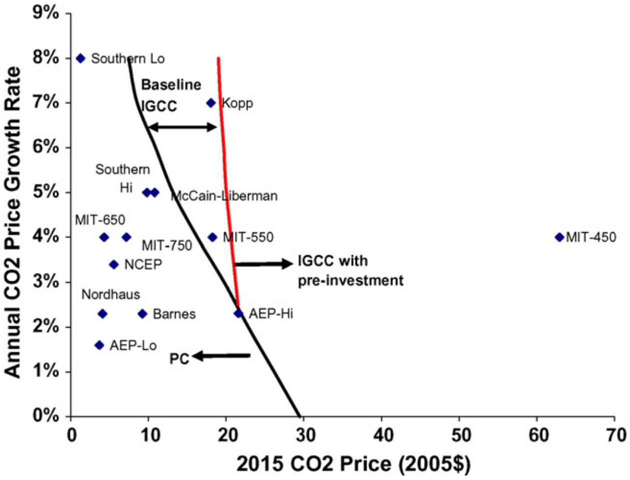

Fig. 3 – Economically optimal technology choice vs. future CO_2 prices.

Table 4 – Probabilistic Comparison of NPV Costs (in millions of \$)

Initial CO_2 price	Probability	NPV costs base case cash flows		NPV costs alternate case cash flows	
		PC	IGCC	PC	IGCC
0	0.15	1224	1314	1224	1356
10	0.2	1484	1613	1484	1617
20	0.25	1745	1816	1745	1848
30	0.2	2006	1866	1926	1898
40	0.15	2211	1907	2029	1934
50	0.05	2285	1948	2060	1969
Weighted sum		1764	1730	1716	1757

Table 5 – Optimal year of retrofit for base case cash flow model

Initial CO_2 price ($)	Baseline PC	Baseline IGCC	Pre-Investment IGCC
15	Never	Never	Never
20	Never	2023	2019
25	Never	2015	2015
30	Never	2015	2015
35	2026	2015	2015
40	2019	2015	2015
45	2015	2015	2015
50	2015	2015	2015

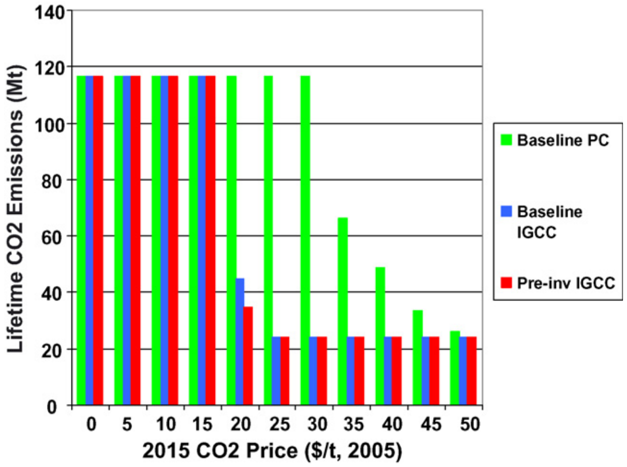

Fig. 5 – Lifetime CO_2 emissions as a function of the initial CO_2 price for a 2% annual CO_2 price growth rate.

4.2. *Impact of technology choice on optimal year of retrofit and lifetime CO_2 emissions*

The second part of the analysis for this study evaluated the impact of technology choice and pre-investment on the expected year of retrofit and lifetime CO_2 emissions of the plant. This analysis determined what the economically optimal year of retrofit is for each of the three cases under the full range of initial carbon price levels and annual rates of increases. The model iteratively determines the optimal year of retrofit for each carbon price scenario.

To determine the impact of the technology choice on the lifetime CO_2 emissions of the plant, the year of retrofit was then used to determine the lifetime CO_2 emissions, with higher emissions occurring before the retrofit, and much lower emissions occurring after the retrofit.

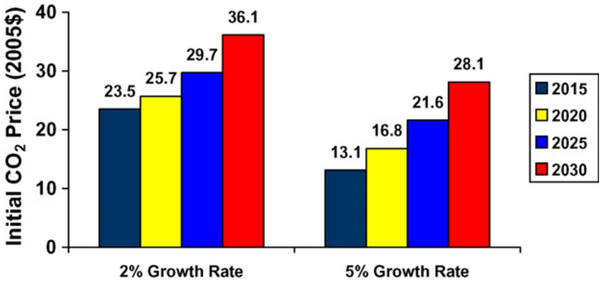

Fig. 6 – Sensitivity to year of initial CO_2 price implementation on economically optimal technology choice.

Table 5 illustrates the impact of the initial carbon price on the optimal year of retrofit for a carbon price growth rate of 2%. This table illustrates that unless there is a high initial carbon price PC plants will not retrofit. The IGCC plants will retrofit at a much lower carbon price. There is little difference in the year of retrofit between the baseline and pre-investment IGCC cases.

These results provide significant insight into the concept of CO_2 'lock-in' (see Fig. 5). First, a high enough carbon price is required for lifetime CO_2 emissions to be reduced. An IGCC plant is expected to have a large (50–70%) reduction in lifetime CO_2 emissions if the initial CO_2 price falls within a moderate (\$20–35/t CO_2) range. At CO_2 prices below \$15/t CO_2, the difference in lifetime CO_2 emissions between the PC and IGCC plants are similar, with the PC being more economical. At CO_2 prices above \$35/t CO_2 the difference in lifetime CO_2 emissions are again similar, but with the IGCC being much more economical.

4.3. *Impact of delayed initial CO_2 price implementation*

As a sensitivity test, an analysis was performed with a carbon prices beginning in 2020, 2025, and 2030 (versus 2015 in the base case). The impact of this analysis on the initial CO_2 price at the crossover point for the optimal technology choice is illustrated in Fig. 6. The impact of the delayed implementation of the carbon price is to increase the initially required carbon price level at which an IGCC plant becomes more economical than a PC plant. It can be seen that the increase is non-linear, growing in size for each subsequent 5-year delay.

5. Conclusions

Key conclusions of this paper are:

- The concept of 'capture-ready' is not a specific plant design; rather it is a spectrum of investments and design decisions that a plant owner might undertake during the design and construction of the plant.
- For the range of future carbon prices that would be generated by policy options currently under consideration, significant pre-investment for CO_2 capture and storage is not

economically justified. However, low cost options (e.g., leaving extra space) should be considered.

- The choice of power plant technology is very dependent on both the cash flow models (i.e., the relative costs of the technologies) and the assumed future CO_2 price trajectory.
- CO_2 "lock-in" is a function of future CO_2 prices. At low CO_2 prices, CO_2 "lock-in" occurs in all plants regardless of the technology. At high CO_2 prices, all plants will lower CO_2 emissions (through CCS or by shutting down), but there will be large differences in the costs. At moderate CO_2 prices, the capture-ready concept can help to avoid CO_2 "lock-in."
- The longer the delay in establishing a CO_2 price after a plant is built, the higher the CO_2 price needs to be to justify the "capture-ready" concept.

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