Repowering Coal-Fired Power Plants for Carbon Dioxide Capture and Sequestration - Further Testing of NEMS for Integrated Assessments

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Disclaimer

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Acknowledgements

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Summary

This study is a followup to an exploratory study on the use of the National Energy Modeling System (NEMS) of the Energy Information Administration for undertaking integrated assessments of the retrofitting of coal fired power plants for carbon dioxide capture and sequestration (CCS). Unlike the previous study which envisioned retrofitting by means of an advanced amine process, this study envisions repowering by means of Integrated Gasification Combined Cycle (IGCC) technology configured for capture and sequestration of carbon dioxide (IGIS). For repowered plants, cost and performance factors were based upon generic IGIS in a "brownfield" setting, wherein the site's ancillary equipment and infrastructure is used, but not its existing steam turbine.

From a modeling perspective, the logic required to account for retrofitting or repowering in NEMS is similar, and the modifications made to enable the endogenous determination of the tradeoffs among repowering, retirement, and the purchase of carbon emission allowances (CEA) are as described in the report of the previous retrofitting study[1]. The modifications extended the standard retrofitting model from a 3-P (three pollutant—sulfur oxides, nitrogen oxides, and mercury) to a 4-P formulation (the fourth pollutant being carbon dioxide) and accounted for capacity and heat rate penalties. It was possible to stay within the existing modeling structures of NEMS.

However, differences do exist in how cost and performance impacts are properly accounted for. In retrofitting, cost factors are correlated to plant characteristics, such as heat rate, and are then added incrementally to existing cost factors. The cost and performance factors for the repowered plant are decoupled from plant characteristics and are used to overwrite existing factors.

The cost and performance factors for the repowered plant are scaled to the projections for a generic greenfield IGIS plant, specifically those associated with the goals of the Fossil Energy Research and Development (FE R&D) IGCC and Sequestration Programs[2]. A generic discount factor is applied to the greenfield capital cost factor to account for savings associated with a brownfield installation. For the purposes of this study, a single discount factor is applied throughout the fleet, but repowering is expected to involve several site specific factors.

Using a carbon tax formulation of the Annual Energy Outlook (AEO) 2007[3], the expected sensitivities were observed with respect to cost factors and constraints on carbon emissions (CEA price). The penetration of repowering was not observed to any extent until CEAs exceeded 30 \$/MTCO_2e (metric ton CO_2 equivalent). In addition to the generic cost and performance factors for greenfield IGIS, baseline cost factors included a capital cost discount

[1] Retrofitting Coal-Fired Power Plants for Carbon Dioxide Capture and Sequestration - Exploratory Testing of NEMS for Integrated Assessments, DOE/NETL-2008/1309, R. A. Geisbrecht, January 18, 2008.
[2] Fossil Energy R&D Benefits Analysis Report, NETL Report, 2007.
[3] Energy Information Administration, "Annual Energy Outlook 2007," DOE/EIA-0383(2007), February 2007.

factor of 15 percent for brownfield sites[4] and 4 \$/MTCO$_2$e for transportation, injection, and measurement, monitoring, and verification (MMV)[5].

Applying the repowering option at a CEA of 45 \$/MTCO$_2$e, about 100 GW of capacity was repowered through 2030, in addition to reductions in coal plant retirements and nuclear builds of about 75 GW and 100 GW, respectively. Rather than a proportional reduction consistent with the other greenfield technologies, builds of greenfield IGIS increased slightly with the repowering option, and the combined builds of brownfield and greenfield IGIS increased by about 110 GW.

The ability to endogenously model competition and synergies between brownfield and greenfield installations is a noteworthy aspect of the approach used in this study. Competition arises when retirements are avoided though repowering, thereby reducing the market for greenfield capacity additions. Synergies occur directly through the shared learning rate of the underlying IGIS technology which is favorably impacted by both greenfield and brownfield installations. Synergies also occur indirectly through diminished learning in the alternative technologies with reduced deployments which compete with greenfield IGIS, such as nuclear[6]. Without repowering options, NEMS only allows for greenfield technologies to compete for growing demand and/or replacement of retired capacity[7].

Electricity generation capacities of IGIS repowered plants observed in this exploratory study are likely an upper bound because site-specific factors were not included in the generic model, and cost and performance factors were based on advanced IGIS per FE R&D Program goals, which relate more to R&D goals than predictions of actual technological progress.

Introduction

This paper presents an exploratory attempt at an integrated NEMS-based analysis of repowering the fleet of coal-fired power plants (as described in the detailed plant data base in NEMS) for the purpose of CO_2 capture and sequestration. IGIS is the envisioned repowering technology. A similar study was previously completed for retrofitting with an advanced amine-based process. Both studies assume generic cost and performance factors are valid across the fleet, without detailed consideration of site specific factors.

The IGIS technology was selected for this repowering study because IGIS is the essential FE technology for CCS and offers analysis on the competition and synergies between brownfield

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[4] "Brownfield IGCCs as an Option in the National Energy Modeling System (NEMS)," OSAP White Paper, February 2007.

[5] RDS, LLC, "Cost and Performance Baseline for Fossil Energy Plants – Vol.1, Bituminous Coal and Natural Gas to Electricity," DOE/NETL – 2007/1281, Final Report, May 2007.

[6] Only the indirect form of synergy was operative in this study since endogenous learning for IGIS was not possible with the exogenous inputs that were used for IGIS cost and performance factors.

[7] A limited analysis of brownfield IGIS could be made with the standard form of NEMS, but only for the special circumstance when new builds, using brownfield parameters, are less than total retirements, along with the assumption that other technologies are not competitive with IGIS for the brownfield site.

and greenfield applications. The cost and performance projections for greenfield IGIS are used as a basis for the corresponding factors for a brownfield application.

Data Development

Cost and Performance Factors

Cost and performance factors for greenfield IGIS and IGCC were equated to projections in the 2007 Annual Update to the FE R&D Program Benefits Analysis (Figs. 1 - 4)[8]. From 2015 through 2030, both capital cost and heat rate for IGIS are about 25 percent greater than for IGCC. Even for “sequestration penalties” significantly greater than 25 percent, a later model shows IGIS is preferable to IGCC for repowering when CEA prices are high enough to support any repowering over simple purchase of CEAs (generally greater than 30 $/MTCO$_2$e). Consequently, NEMS simulations were focused on repowering by IGIS rather than IGCC.

Given that a 4 $/MTCO$_2$e cost for CO_2 transportation, injection, and MMV is reportedly included in the variable Operations and Maintenance (O&M) cost factor for the greenfield IGIS estimate, this cost was not explicitly added as it was in the previous retrofit study.

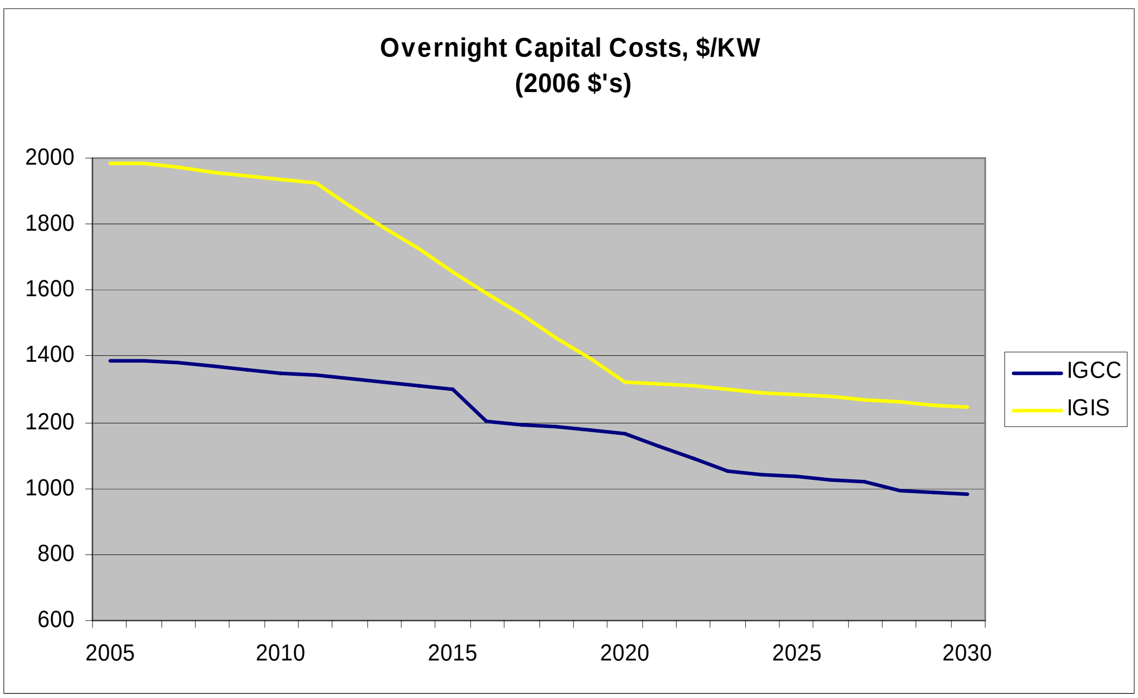

Figure 1: IGIS capital is about 25 percent higher than IGCC capital in the important 2015-2030 time frame.

[8] The 2007 Benefits Analysis was not finalized at the time of this study, so slight differences between the factors shown here and the factors finalized for the Benefits Analysis may exist, but the factors shown are typical.

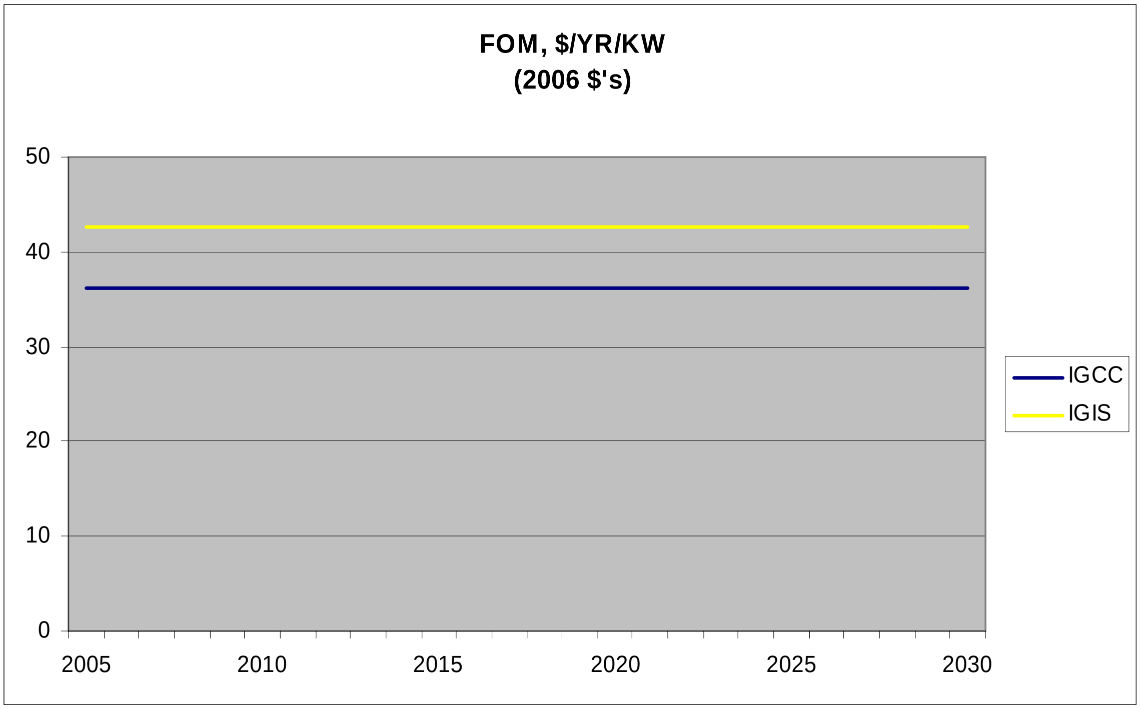

Figure 2: Fixed Operation and Maintenance (FOM) costs (excluding annualized capital costs) are significantly smaller than the annualized costs for recovery of capital.

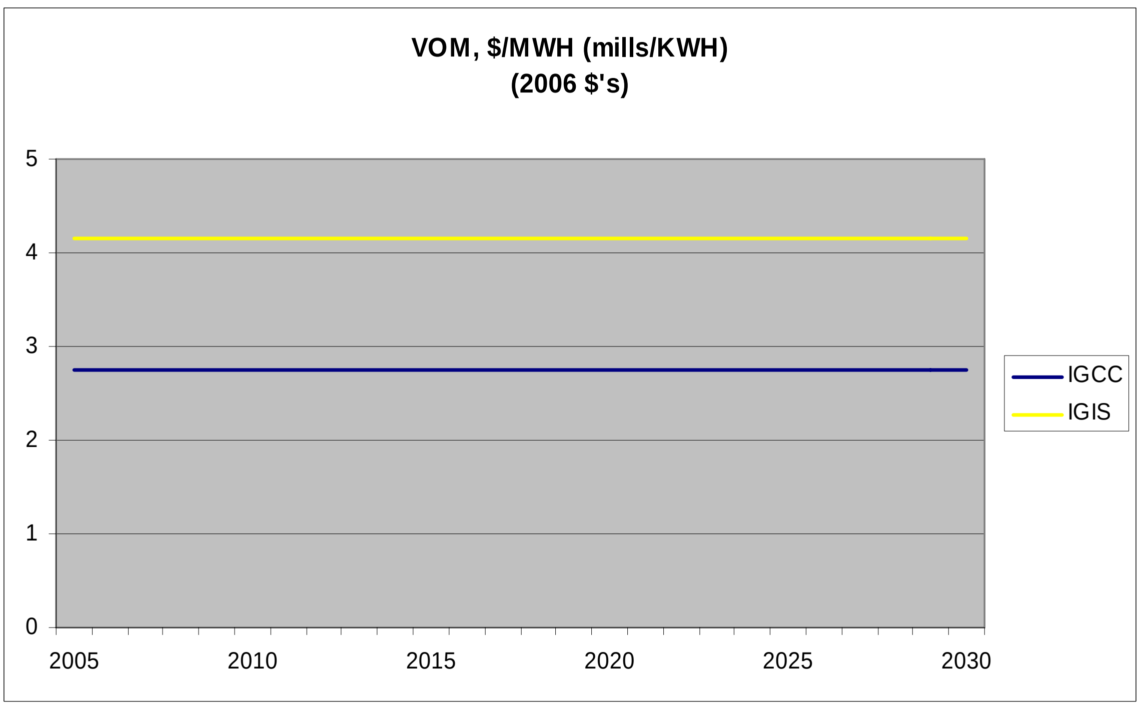

Figure 3: Variable Operation and Maintenance (VOM) costs for IGIS reportedly include 4 $/MT$CO_2$e for CO_2 transport, injection, and MMV.

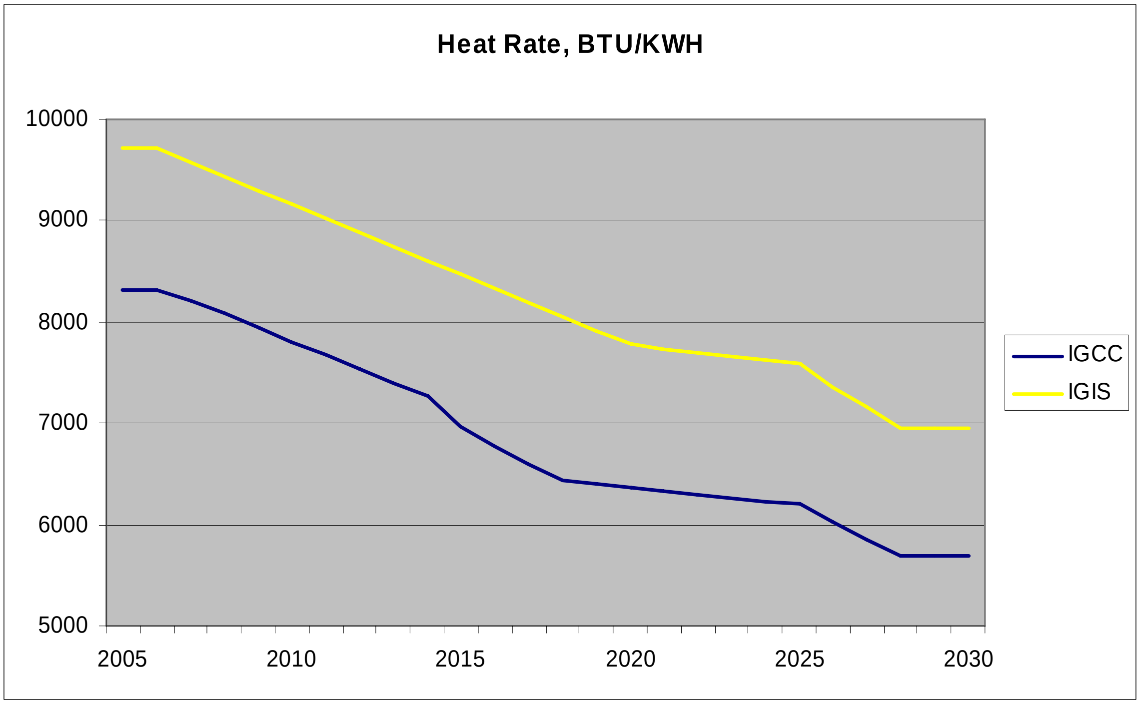

Figure 4: IGIS heat rate is about 25 percent higher than IGCC heat rate in the important 2015-2030 time frame.

Brownfield Discount Factor and Generic Process Assumption

The repowering process is assumed to be "rubberized" in that the original plant output capacity is unchanged by repowering. This implies that cost and performance factors for the repowered plant are continuously scalable over the range of existing plant capacities without penalties in cost or performance.

On the basis of this assumption, a single brownfield discount factor is used throughout the fleet. Sensitivity studies varied this factor (percentage savings of greenfield capital cost at a brownfield site) over the range of 15 percent to 50 percent[9]. The lower end of this range is comparable to the reported estimates based on the use of a site's existing ancillary equipment and infrastructure, but not major equipment like the steam turbine. The upper end of this range was primarily used to test model behavior.

Model Development

A retrofit model for CCS is not a standard part of the public version of NEMS, so the only options for coal plants in carbon-constrained scenarios are either the purchase of CEAs or their retirement and replacement by new lower carbon emission or carbon neutral plants. To undertake integrated fleet-wide assessments with carbon emission constraints, modifications to

[9] Model calculations show the importance of this parameter is bounded and related to factors, including the CEA price, that determine the relative importance of capital in the levelized cost of electricity.

the NEMS code and input files were needed, as described in a separate NETL report[10]. Certain changes peculiar to repowering versus retrofitting are noted in the following:

Code Changes

UECP.F - The changes were confined to the two subroutines EP$COAL and EPO$COAL. For a repowering option, coding was added to copy current-year cost and performance factors for a greenfield IGIS plant into those for the repowered plant, with the exception that overnight capital cost was multiplied by the brownfield discount factor.

Instead of adding incremental cost factors to the corresponding retrofit cost categories wherever a CO_2 repowering is indicated in the code as part of a retrofit package, the cost categories were overwritten by the corresponding factors for brownfield IGIS. Capacity penalties were set to zero in accord with the generic process assumption and heat rate penalties were back-calculated to match the brownfield IGIS heat rate (capacity and heat rate penalties are used in various constraint-row and free-row coefficients revised in the previous retrofit study to account for changes in plant capacity and heat rate due to retrofitting or repowering).

Interpretive Model of CO_2 Retrofit and Repowering Decisions

A simple conceptual model provided context for designing and interpreting the integrated assessments in NEMS. The model was coded in Excel to display all options for retrofitting, repowering, and retiring. The preferred option for any given plant is taken as the option with the lowest levelized cost of electricity. Most importantly, that option depends upon the carbon value (also referred to herein as CEA price, carbon tax, etc.). For a range of carbon values, the levelized cost of electricity was calculated as a function of O&M costs, heat rate, fuel price for the existing plant, and the generic cost and performance factors for retrofitting and repowering options. Sensitivity studies revealed how decisions will tend to depend upon factors such as sequestration penalty, brownfield discount factor, and any of the above plant or process factors.

To the extent possible, model parameter values were used that reflect values likely to be encountered in the NEMS assessments. On this basis, neither retrofitting nor repowering is likely until CEAs exceed 20 $/MTCO_2e$ to 30 $/MTCO_2e$. Additionally, the choice of retrofitting or repowering is dependent on the nature of the existing plant, with a major factor being its heat rate, or age (Figs. 5 - 6). When CEAs reach a level high enough to justify retrofit or repowering options, retrofitting tends to be preferred for lower heat rate plants, while repowering is preferential for older plants with a higher heat rate.

[10] Retrofitting Coal-Fired Power Plants for Carbon Dioxide Capture and Sequestration - Exploratory Testing of NEMS for Integrated Assessments, DOE/NETL-2008/1309, R. A. Geisbrecht, January 18, 2007.

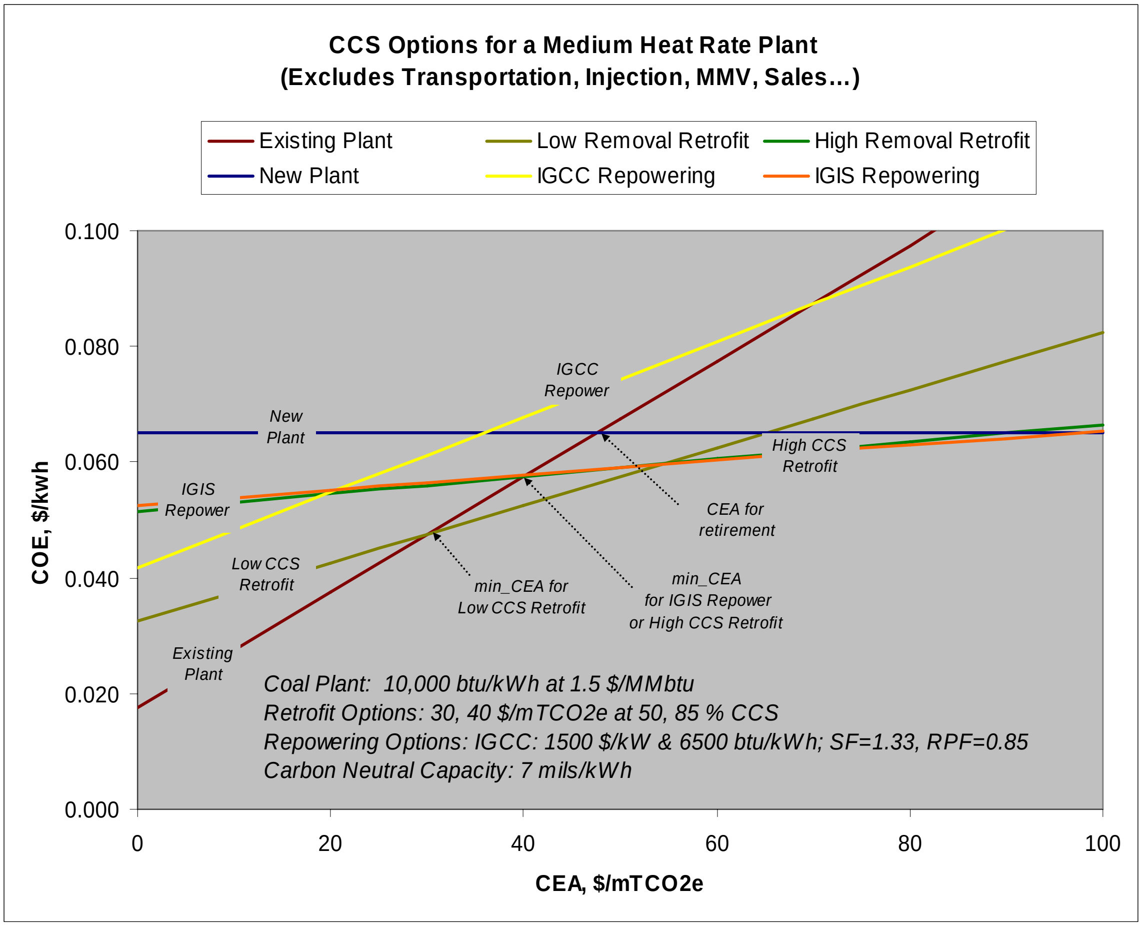

Figure 5: IGCC repowering is competitive with IGIS repowering only at low CEAs, where both are not competitive with simple purchase of CEAs. Retrofitting is more competitive with repowering for medium heat rate (modern) plants. SF = IGIS (capital, heat rate)/IGCC (capital, heat rate); RPF = (1 - repowering discount factor) = brownfield capital/greenfield capital.

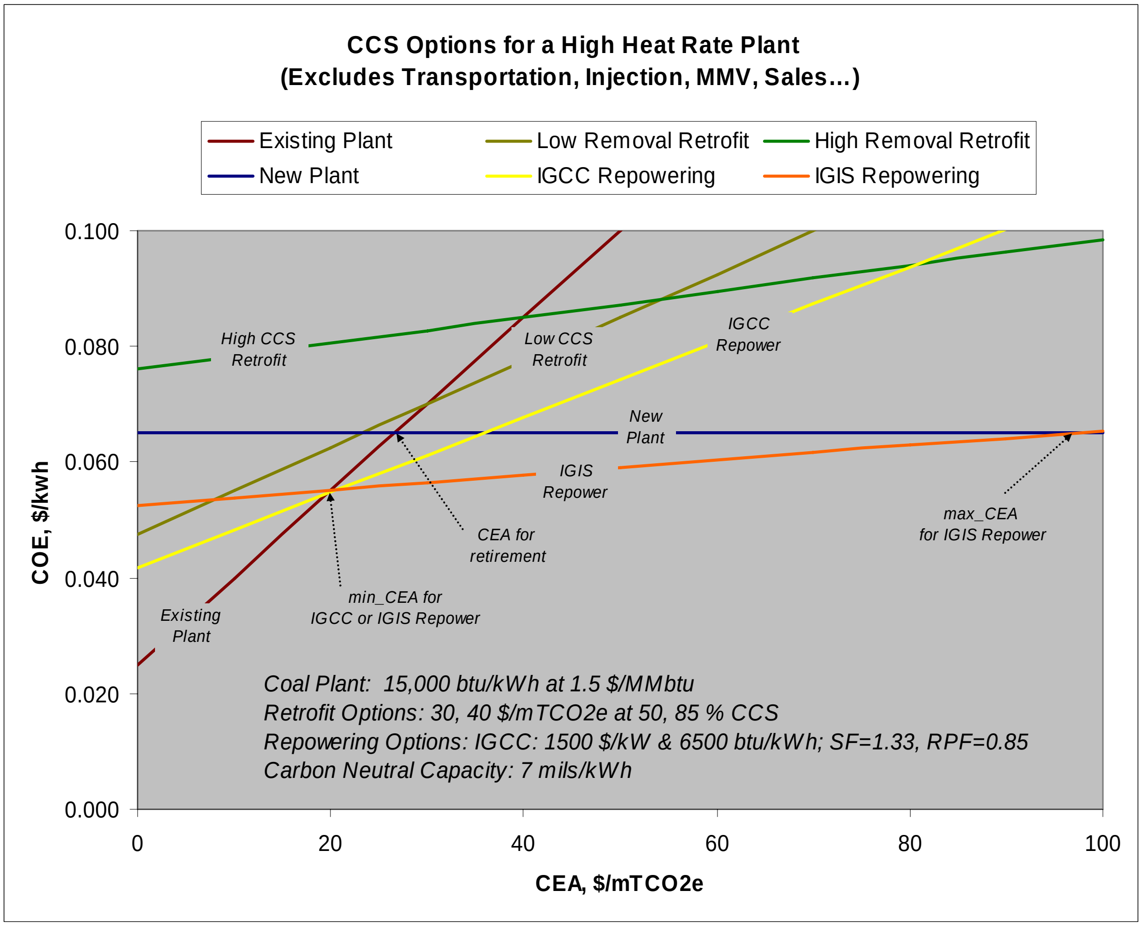

Figure 6: Repowering is more competitive with retrofitting for high heat rate (old) plants. SF = IGIS (capital, heat rate)/IGCC (capital, heat rate); RPF = (1 - repowering discount factor) = brownfield capital/greenfield capital.

As shown for the lower heat rate plant (Fig. 5), the minimum CEA for retrofitting is 30 $/MTCO_2e; the preferred option below 30 $/MTCO_2e is the purchase of CEAs. Retirement is indicated when CEAs exceed 50 $/MTCO_2e in the absence of any options for retrofitting or repowering. With all options for retrofitting and repowering available, the low CCS retrofit (50 percent CCS) is indicated for CEAs between 30 $/MTCO_2e and 50 $/MTCO_2e; above this CEA range, the high CCS retrofit (90 percent CCS) is indicated.

In contrast, the minimum CEA for repowering is 20 $/MTCO_2e as displayed for the higher heat rate plant (Fig. 6). When CEAs reach a level high enough to justify repowering, IGIS is preferred over IGCC for repowering. IGCC is preferred over IGIS for repowering only when CEAs are below the 20 $/MTCO_2e threshold, but then the indicated option is the purchase of CEAs. Retrofitting in any form is not competitive to repowering at any CEA level and in the absence of the IGIS repowering option, retirement is indicated when CEAs exceed 30 $/MTCO_2e.

The marked differences between the cases described above suggest that retrofitting and repowering tend to be best suited to different sets of plants in the fleet, with the former more suited to older, higher heat rate plants and the latter to newer, lower heat rate plants.

Results & Analysis

The penetration of IGIS repowering across the fleet and its impact on plant retirements, CO_2 emission levels, and builds of carbon neutral capacity were a function of the carbon emission tax level. Carbon emission tax profiles were similar to those derived in FE R&D Program Benefits Analyses, which anticipate scenarios related to policies on global climate change (Fig. 7).

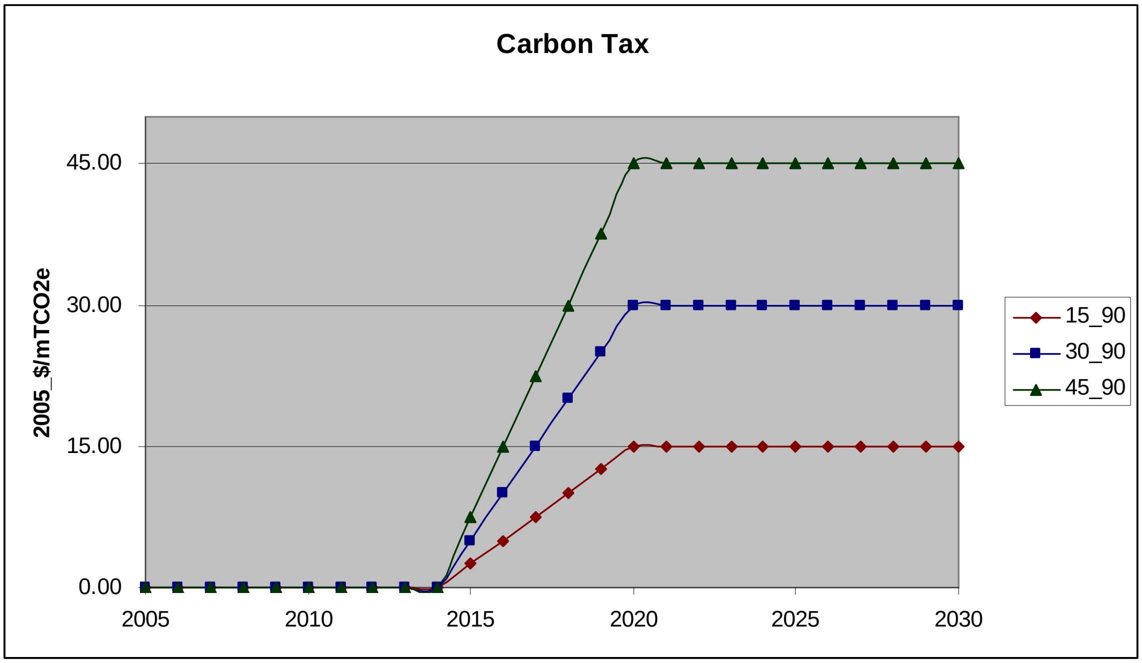

Figure 7: Profiles of carbon tax showing the steep ramp up from 2014-2020.

As in the retrofitting study, the 30 $/MTCO_2e$ case represented a threshold for the repowering option, evident from the relative lack of retirements or retrofits being chosen over the purchase of CEAs (Fig. 8)[11]. At 45 $/MTCO_2e$, significant capacity was either retired or repowered, depending upon the availability of the repowering option. With the repowering option, a capacity of about 100 GW was repowered through 2030, in addition to reductions in both coal plant retirements and nuclear builds of about 75 GW and 100 GW, respectively (Figs. 9 - 10). This is not unexpected since direct extrapolation of the AEO 2007 assumptions to carbon control strategies are known to favor new nuclear builds[12].

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[11] Legend entries of the type 30_IS_85_5 signify a CEA price of 30 $/MTCO_2e$, repowering technology using IGIS, a brownfield discount factor of 15 percent (100-85) applied to greenfield capital costs, and a 5 $/MMBTU tariff on the price of natural gas as delivered to electric utilities.

[12] Energy Information Administration, "Energy Market and Economic Impacts of S. 280, the Climate Stewardship and Innovation Act of 2007," SR/OIAF/2007-04, July 2007.

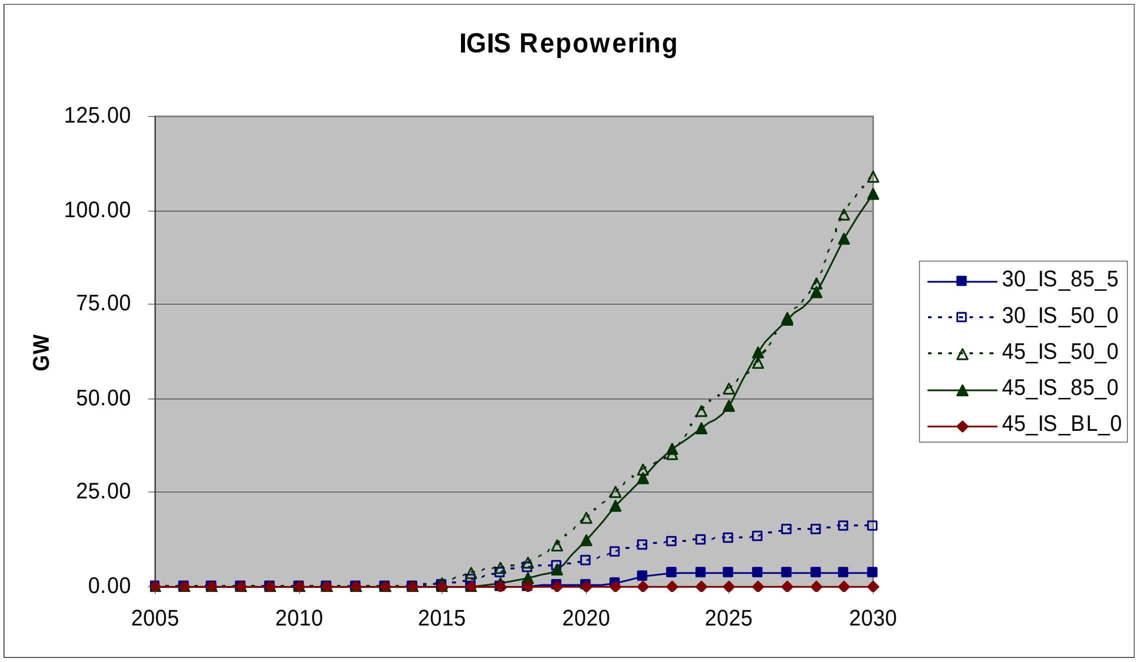

Figure 8: Repowering does not become significant until CEA price exceeds 30 $/MTCO_2e$. Compared to the previous retrofit study, steadier deployment rates probably result from stable technological progress in cost and performance factors for greenfield IGIS, or lack thereof for the advanced amine process in the retrofit study.

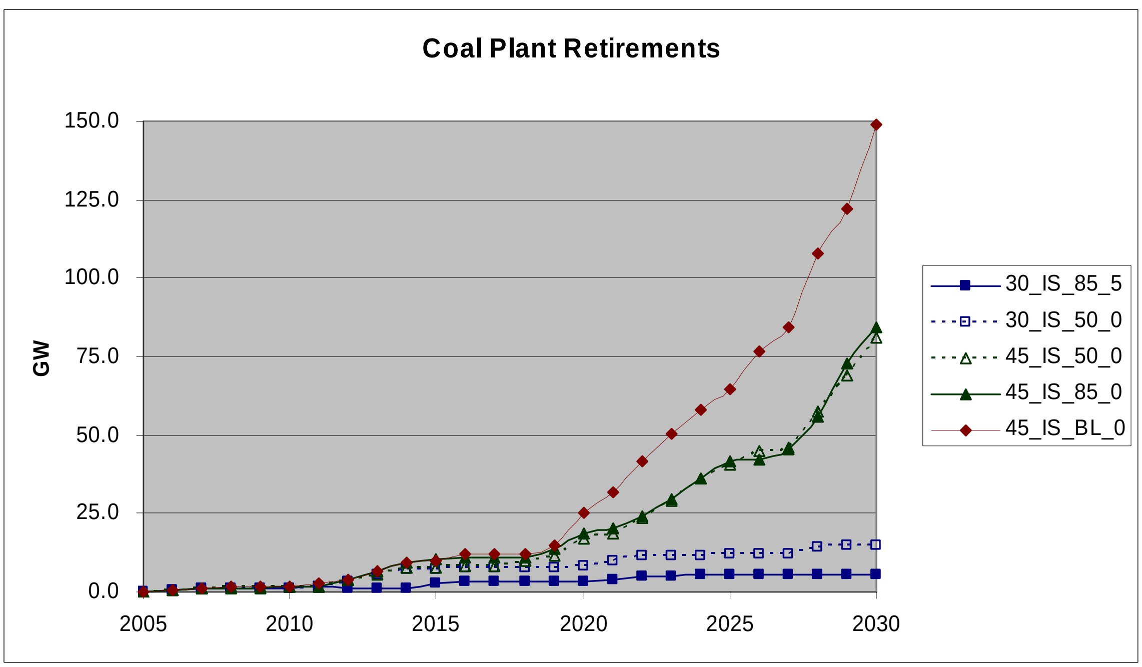

Figure 9: Through 2030, retirements without a repowering option reach 150 GW, nearly half of the fleet in 2007. At 30 $/MTCO_2e$, the influence of gas prices is greater than the brownfield discount factor.

Since IGIS is essentially carbon neutral (90 percent CCS is assumed), CO_2 emissions were comparable to when coal capacity was retired and replaced by lower carbon emission or carbon neutral technologies (Fig. 11). When CEAs exceeded 30 $/MTCO$_2$e, IGIS repowering acted as an alternative pathway for stabilizing emissions and preserving coal-fired capacity (Fig. 12).

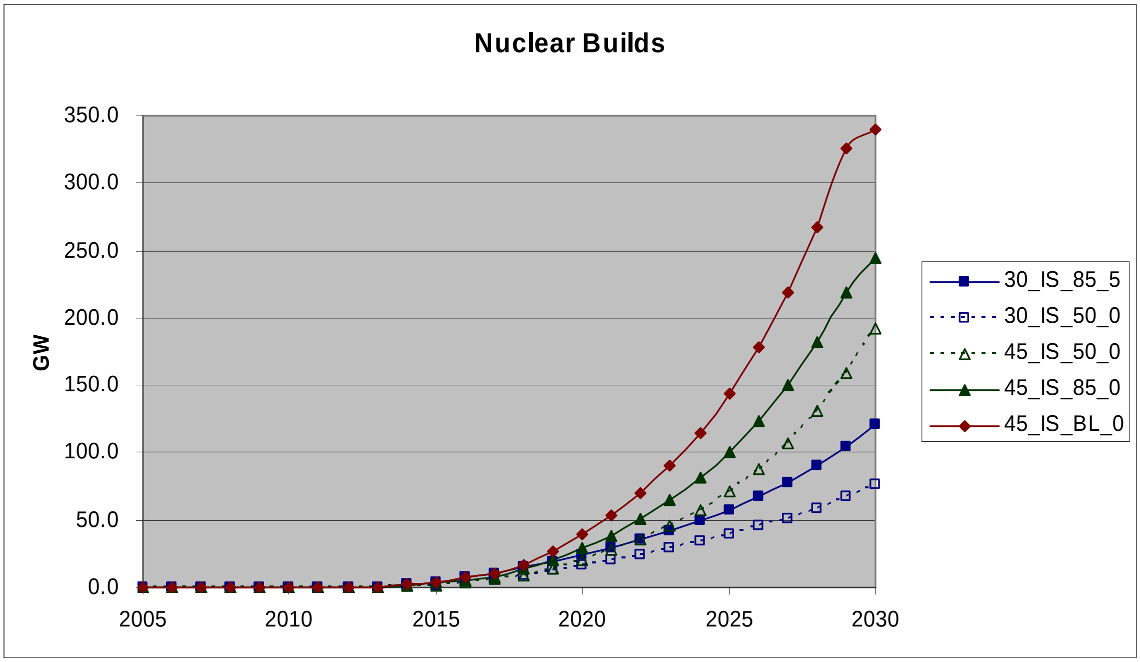

Figure 10: Cost and performance factors for nuclear technology are based on EIA's AEO_2007 projections, without modifications to constrain nuclear builds at high CEA prices.

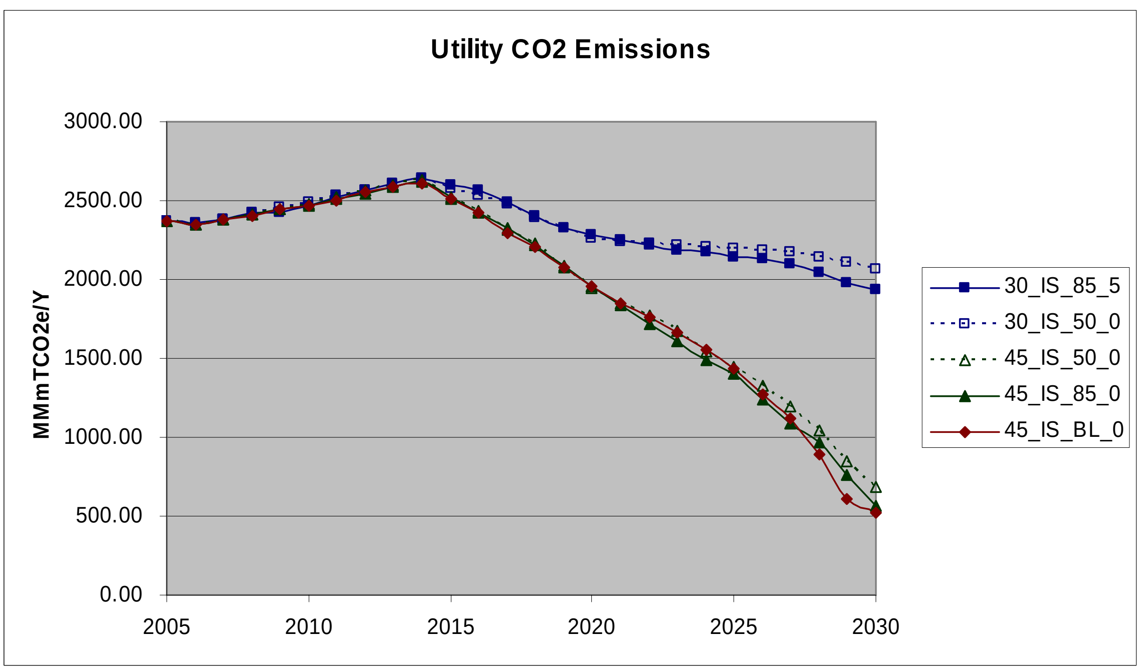

Figure 11: At high enough CEA prices, IGIS repowering acts as an alternative pathway for stabilizing CO_2 emissions.

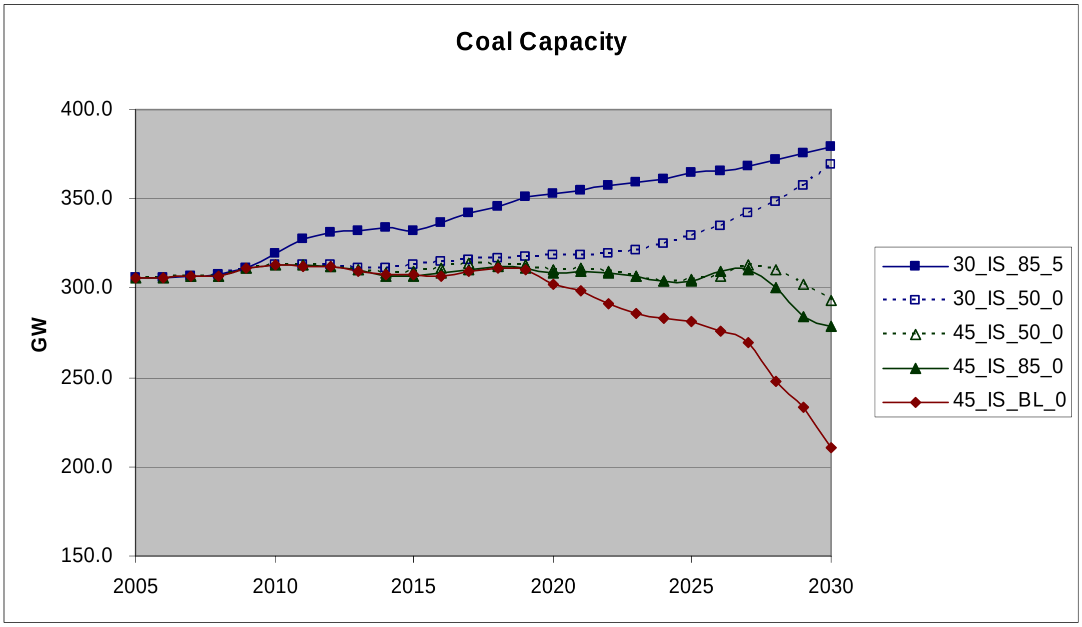

Figure 12: Without a repowering option, extensive retirements are the only option when CEA exceeds 30 $/MTCO_2e.

Greenfield IGIS builds were not reduced in proportion to the decrease in builds of alternative technologies like nuclear; in fact, IGIS greenfield builds increased, albeit slightly (Fig. 13). The combined IGIS builds (brownfield and greenfield) increased by about 110 GW (Fig. 14) with the repowering option. The apparent synergy between brownfield and greenfield IGIS is suggestive of a diminished learning in the alternative technologies with reduced deployments (e.g. nuclear).

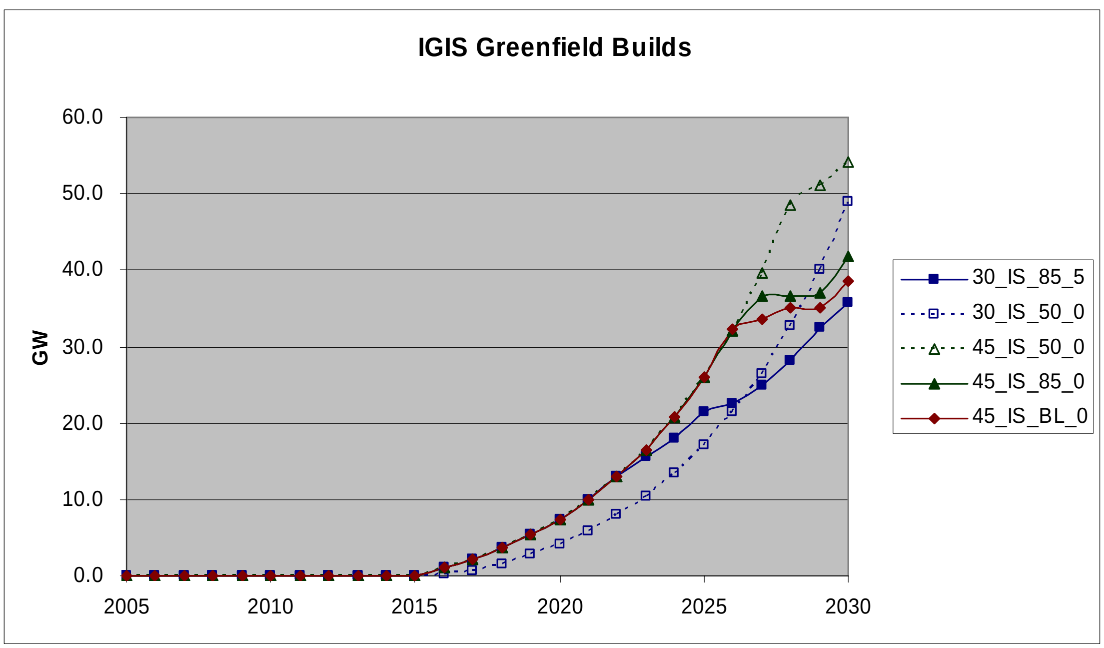

Figure 13: Albeit slightly, Greenfield IGIS builds increase with the repowering option, suggesting a synergy between brownfield and greenfield applications.

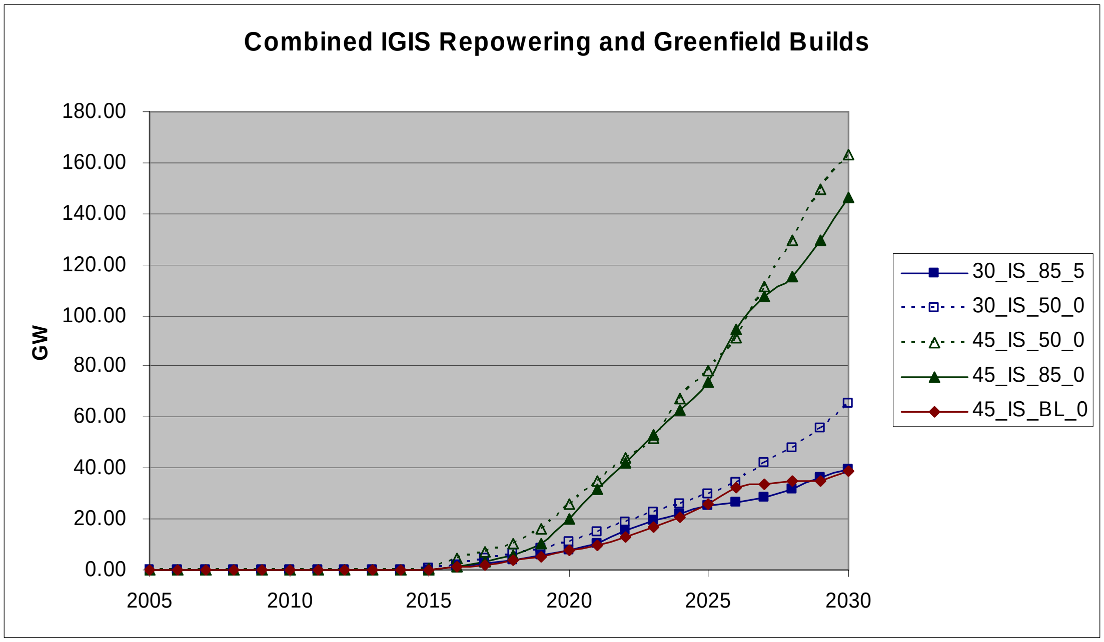

Figure 14: Through 2030, combined brownfield and greenfield IGIS builds increase from 40 GW to about 150 GW with the repowering option.

Conclusions

A NEMS-based approach was devised to carry out integrated, fleet-wide assessments of retrofitting or repowering for CO_2 capture and sequestration using the power plant database in NEMS. Sensitivity tests demonstrated the approach is generally consistent with expectations, including the notion that CO_2 retrofitting or repowering will be relevant at CEA prices above 30 $/mTCO$_2$e. Given that serious climate change policies are likely to involve CEA prices of this magnitude, CO_2 retrofitting and repowering effectively diversifies the alternatives for responding to such policies with respect to the existing fleet of coal fired power plants.

Since the existing fleet of coal fired power plants provides roughly half of the nation's electricity, R&D targeted to improvements in the cost effectiveness of retrofitting and repowering technologies is likely to be of considerable value. The technological advances explored in this study were those implicit in the use of cost and performance goals associated with the FE R&D Programs for IGCC and CCS. The approaches utilized in this study could provide metrics in support of these programs. While the focus was on IGIS repowering, the method is applicable to any retrofitting or repowering approach to CCS.

Based upon an interpretive model executed in this study, the decision to retrofit or repower hinges on plant factors, with lower and higher heat rates being more favorable to retrofit and repowering, respectively. An examination of the competition for repowering and retrofitting portions of the fleet at various carbon values would advance this study. To do so most directly, modifications to another layer of NEMS code will be needed to extend the configuration matrix for coal plants to include added retrofit options[13]. In the interim, a limited analysis is proposed for the circumstances when greenfield builds of IGIS, using brownfield parameters, are less than the retirements of coal fired power plants, which is generally true for CEA prices high enough to cause CO_2 retrofitting or repowering.

[13] Records can be extracted from EMMPRNT.TXT using a Windows "Grepping" tool to determine which plants are retrofitted or repowered in separate simulations, and how the fleet *tends* to partition into candidates for retrofitting or repowering, but this does not allow for competition between retrofitting and repowering.