A Net Benefits Methodology for National Energy Modeling System Simulations of Retrofitting Coal Fired Power Plants for CO_2 Capture and Sequestration

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Acknowledgements

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Summary

This is a followup to papers documenting the exploratory use of the National Energy Modeling System (NEMS) for integrated assessments of either retrofitting or repowering the fleet of coal-fired power plants for the purpose of capture and sequestration of carbon dioxide[1, 2]. The studies were based on published cost and performance projections for advanced amine based scrubbing[3] as applied post combustion to an existing pulverized coal-fired plant and advanced Integrated Gasification Combined Cycle with Carbon Capture and Storage (IGCC-CCS) as a brown-field construction on the existing site, respectively.[4]

Both studies confirmed the workability of extending NEMS for integrated assessments of retrofitting or repowering existing power plants, yielding trends in penetration for retrofitting or repowering that were consistent with estimates. An apparent anomaly was observed though, in that electricity prices increased, rather than decreased, with the penetration of retrofitting or repowering installations. Since the average price of electricity to all consumers is a standard metric in R&D program benefits analyses, work was done to identify the underlying factors and understand the implications.

Broadly speaking, there are at least three underlying factors that could be the cause of the observed price trends. First, retrofitting or repowering could have the result of shifting the split of net benefits in favor of producer surplus over consumer surplus (a *net benefits phenomenon*). Secondly, imperfect decision making in the real world could be embedded in NEMS by intention (a *modeled decision*). Finally, an unintended inconsistency could exist in the retrofit submodule as adapted for carbon capture and sequestration (a *coding inconsistency*). Code revisions and a methodology to estimate net benefits from standard NEMS output were devised to systematically assess each of these factors.

Shifting of net benefits in favor of producer surplus was observed in both studies, with an accentuated effect in the retrofitting study, which involved a significant capacity derating of about 30 percent, suggesting that capacity margins for peaking are adversely affected. On the basis of net benefits analysis, retrofitting acted as a breakeven alternative pathway for reducing CO_2 emissions from the fleet of coal fired power plants, but with an added cost to consumers in the form of a diminished surplus. Repowering also acted as a breakeven alternative pathway for reducing CO_2 emissions, but without added costs to consumers.

Due to the observed differences between these two major pathways for managing the fleet of existing coal-fired power plants to meet imposed carbon reductions, a follow-up study is proposed to perform an integrated analysis in which both pathways compete with each other.

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[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] Repowering Coal Fired Power Plants for Carbon Dioxide Capture and Sequestration – Further Testing of NEMS for Integrated Assessments, DOE/NETL-2008/1310, R. A. Geisbrecht, January 23, 2008.
[3] RDS, LLC, and Alstom Power Inc., "Sequestration for Existing Power Plants Feasibility Study," ME-AM26-04NT41817.401.01.01.003, Final Draft Report, Oct. 31, 2006.
[4] Fossil Energy R&D Benefits Analysis Report, OSAP Report, 2007.

Underlying assumptions of the previous studies would of necessity be sharpened; in particular those related to plants that are unsuitable for retrofitting or repowering due to site specific factors, reconciliation of commercial cost factors as used in the retrofitting study with R&D goals as used in the repowering study, limits on how much capacity can be retrofitted or repowered in any year, and the timing of possible carbon control policies in relation to the availability of certain technologies (CO_2 sequestration, IGCC, etc.). A key issue to be addressed will be the commercialization of IGCC-CCS technology in time to have an impact on the disposition of existing coal-fired power plants if a major climate change policy is adopted in the United States.

Background

Disposition of existing coal-fired power plants is a major issue in strategies to cap the emissions of greenhouse gases in global climate change scenarios. In the market based context whereby emissions are controlled by a carbon emission allowance price (as set by cap-and-trade or imposed carbon taxes), four basic options are: purchase of emission allowances (status quo), retirement, retrofitting, and repowering.

The preferred option for any given plant is expected to depend on a plant's characteristics such as its age, configuration with respect to other emission controls, heat rate, capacity, and site specific factors; hence any integrated assessment of options will require a plant level description of the fleet. NEMS is an integrated assessment tool which incorporates a plant level data base, but the extant version only allows for the first two options. Since we are interested in the prospects for retrofitting or repowering (R&D) programs, studies were done on the workability of extending NEMS to these two options:

1. Retrofitting
   This analysis assumed that costs for retrofitting existing plants with an advanced amine process are generically related to those estimated in a design study for a specific, typical PC plant.

2. Repowering
   This analysis made a similar assumption that costs for repowering existing plants with IGCC-CCS are generically related to those envisioned as goals in the DOE R&D Programs for IGCC and CO_2 Sequestration.

Both studies confirmed the basic workability of extending NEMS to include retrofitting and repowering options. Trends in the penetration of either option were consistent with expectations, including the impact of major variables such as level and timing of carbon emission allowance prices. At high enough carbon emission allowance prices (generally greater than 45 $/mTCO$_2$e), a substantial portion of the fleet is retrofitted, or repowered, and massive retirements are avoided. The penetration of these options, and their impact on emissions, are basic metrics from the standpoint of R&D program goals and benefits.

Unfortunately, expected trends were not observed for all metrics, in particular for one routinely used in R&D program benefits analyses–the impact on weighted electricity price to all consumers.[5] With respect to this metric an anomaly was observed in both studies in that electricity prices increased rather than decreased with penetration.

Introduction

A consistent, albeit slight, increase in the average price of electricity to all consumers as retrofitting or repowering of existing coal-fired power plants penetrates the fleet is somewhat unexpected in that decisions to retrofit or repower are made in the ECP (electricity capacity planning) submodule of NEMS, which is formulated to minimize total costs of electricity production. Minimizing the total cost of production is not necessarily equivalent to minimizing the average price to all consumers. If the split of net benefits is shifted to favor producer surplus over consumer surplus, then the observed results would naturally arise as a net benefits phenomenon. Otherwise the observed results must be assumed to arise from either a *modeled decision* or a *coding inconsistency*.

For our purposes, a *modeled decision* is one that is presumably an intended feature in NEMS to reflect imperfect decision making in the real world. Modeled inconsistencies are possible since capacity planning is done with a limited degree of foresight (explicit planning horizons of less than a few years are typical). Furthermore, capacity planning in the ECP submodule uses an internal dispatch model that is separate from the model actually used in the EFD (electricity fuel dispatch) submodule.

A *coding inconsistency* is defined as an inconsistency between the code and the presumed intent of the model. Some subtle inconsistencies were noted in a review of the code, related to the interfacing of the retrofit submodule to the ECP submodule. Whereas the retrofit submodule is essentially at the plant level, the ECP submodule uses aggregated plants (ECP types). Code revisions were devised to eliminate these inconsistencies as a factor in the observed price trends. Since these revisions are largely technicalities, they are documented in an appendix to this paper.

To identify net benefits as an underlying factor, changes in both producer and consumer surplus need to be extracted from the simulations and summed to estimate the net benefits of retrofitting or repowering relative to a baseline case without these options. Persistent negative net benefits throughout the forecast horizon could be an indication of the effects of a modeled decision or a coding inconsistency. Since producer and consumer surplus calculations are not included in NEMS, a methodology to estimate these from standard NEMS output was devised. The methodology used herein is a simple estimation method for changes in pair-wise comparisons when the assumption of a common demand curve is valid. The method is not being proposed as a rigorous method for total surplus determinations from a single simulation.

[5] Directly related to changes in net consumer surplus, this metric combines with changes in net producer surplus to yield changes in net benefits.

Electricity Price Trends in Retrofitting and Repowering

Trends for the average price of electricity to all consumers as a function of penetration by retrofitting or repowering options are summarized in Figures 1 – 4. Instead of noticeable reductions in price, consistent (albeit slight) increases occur with penetration. The effect is more pronounced in the retrofitting case, perhaps due to different assumptions for cost and performance of the technologies (significant capacity deratings are involved in the retrofitting study).

Since retrofitting or repowering decisions are made in the ECP (electricity capacity planning) submodule that is designed to minimize total production costs over the planning horizon, the observed trends are somewhat surprising, with implications that depend on the underlying factors. A net benefits perspective was adopted as a first step in gaining an understanding of these factors.

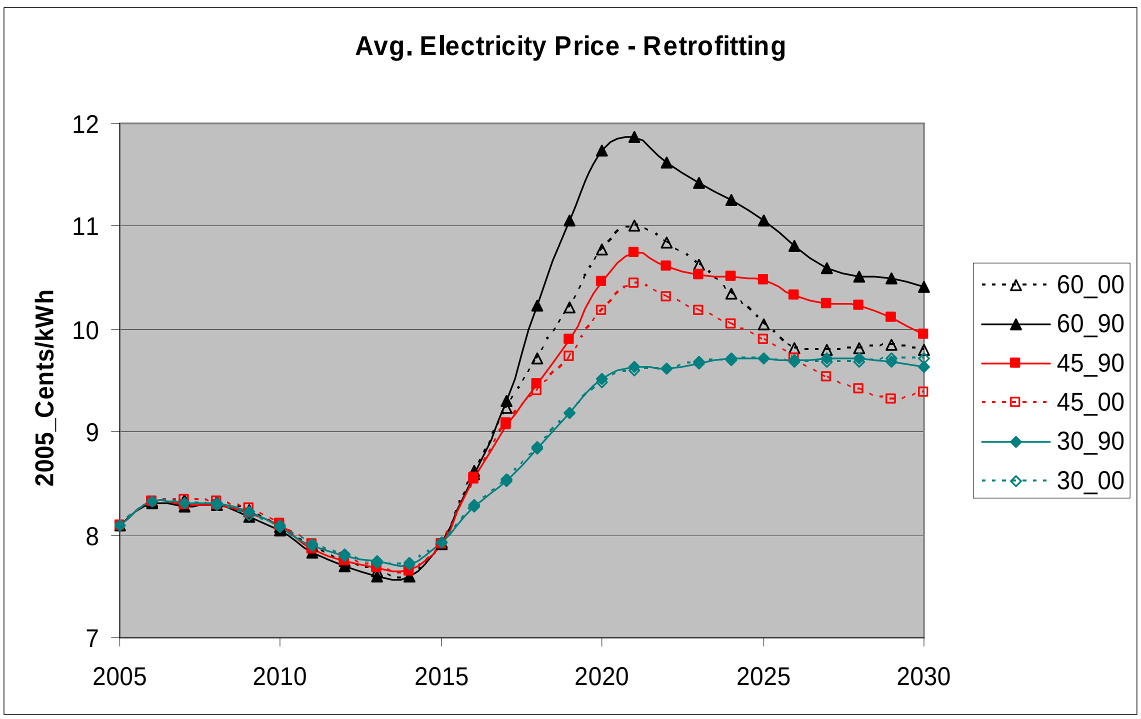

Figure 1. Average Electricity Price to All Consumers in the Retrofitting Study. Prices increase rather than decrease with penetration. Legend entries of the type 30_90 signify a nominal carbon value (carbon emission allowance price or carbon tax) of 30 $/mTCO$_2$e and 90 % removal of CO_2; 00 signifies a baseline with no retrofitting option.

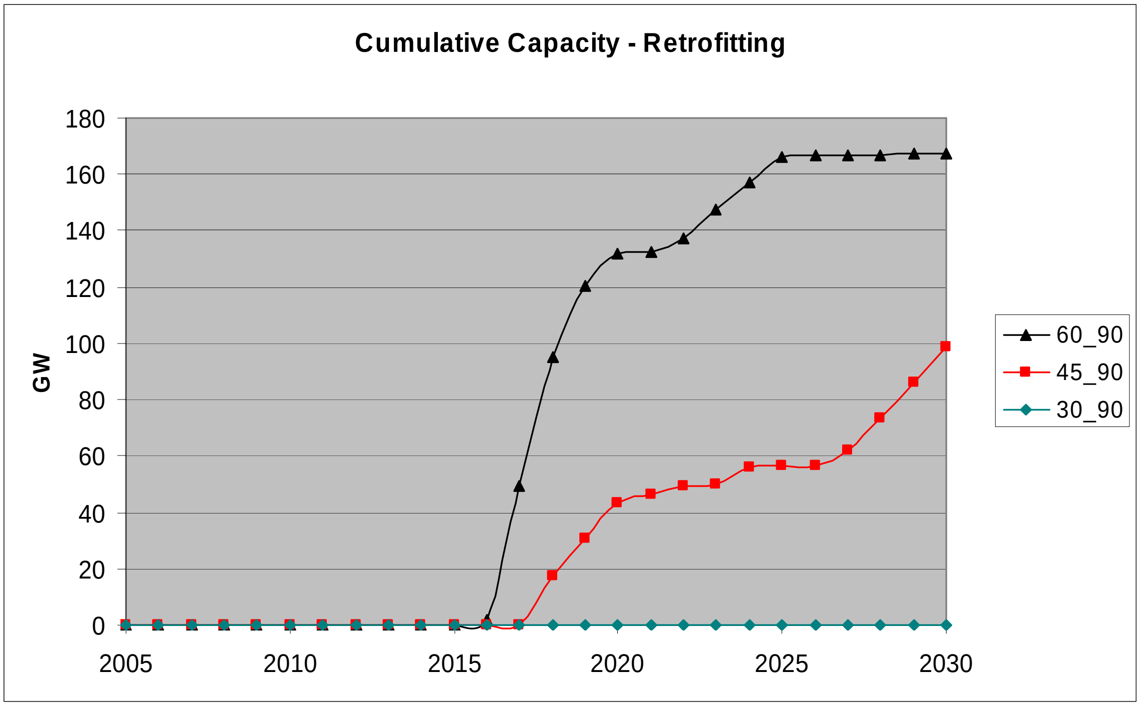

Figure 2. Cumulative Capacity Retrofitted. Penetration is strongly influenced by carbon value. In these hypothetical case studies, retrofits are still being made at 2030 at 45 \$/mTCO_2e , but at 60 \$/mTCO_2e, a plateau is apparent after 2025.

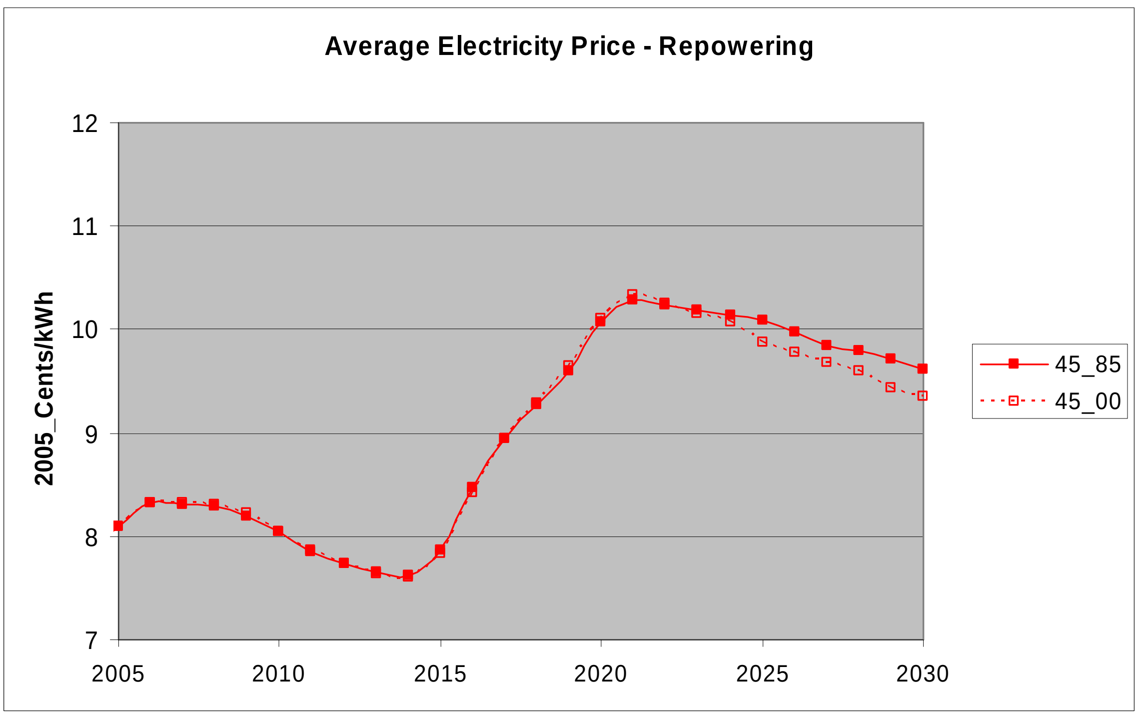

Figure 3. Average Electricity Price to All Consumers in the Repowering Study. Price trends are similar but less pronounced than in the retrofit study. Legend entries of the type 45_85 signify 45 \$/mTCO_2e and brownfield capital costs that are 85 % of greenfield (brownfield discount factor of 15 %); 00 signifies a baseline with no repowering option.

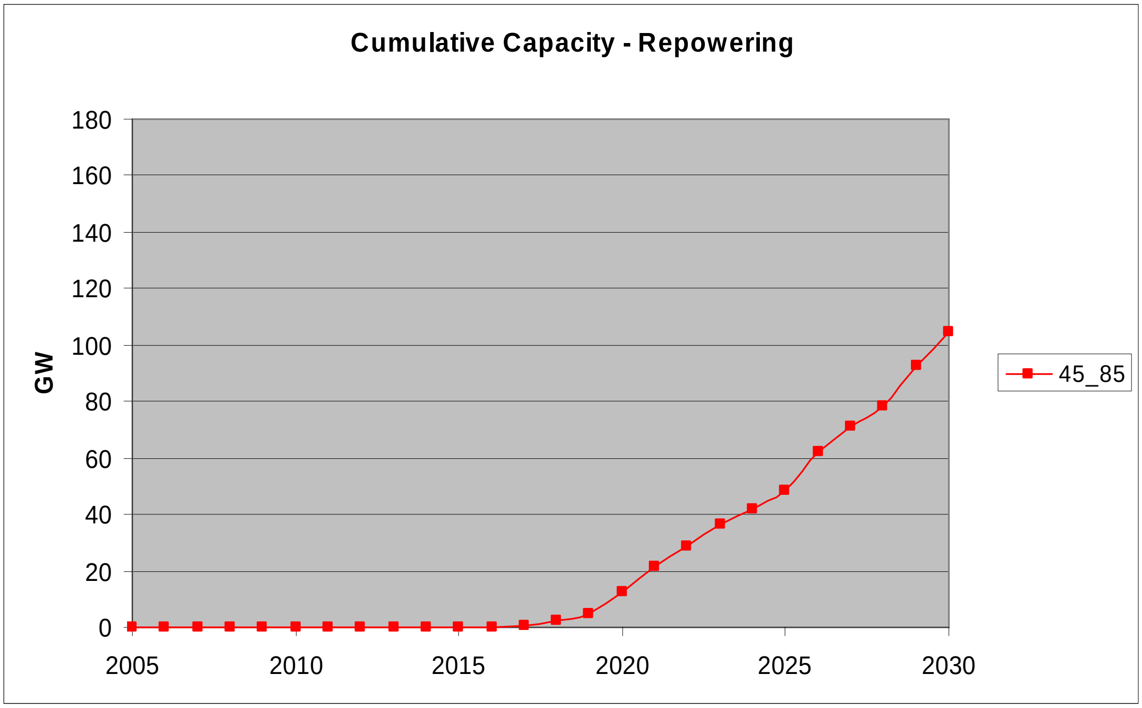

Figure 4. Cumulative Capacity Repowered. Penetration is more gradual than in the retrofit study, reaching almost 33 % of the initial fleet by 2030 in this hypothetical case study.

Net Benefits Methodology

The methodology used herein is a simple estimation method for changes in pair-wise comparisons, in which we are generally interested only in *changes* relative to a base case with a common demand curve (changes from the base case are largely confined to the supply side). Hence, we can assume that the parts of surplus calculations needed for the calculation of absolute values from single simulations (the initial balance of unamortized capital for generation, the value of electricity to consumers, etc.) cancel by differencing, since they are common factors to both the base case and test case.

By definition, changes in producer surplus and consumer surplus are combined for an estimation of net benefits (change in total surplus). Since changes in producer revenue and consumer expenditures are the same and cancel in this approach, an estimate of net benefits is given directly by the change in producer costs, subject to a minor correction factor[6].

In the following, supply and demand curves relate price, **P**, as a function of quantity, **Q**, as shown in Figure 5. Also shown in Figure 5 are "price" curves that allow for sales at prices other than the marginal price, $\hat{\mathbf{P}}$. Net benefits analysis requires a determination of specific areas under the supply, demand, and price curves. In the following terminology, A(P) represents the integral

[6] Note the correction factor is zero for $Q_2 = Q_1$ and generally minor for practical purposes whereby $Q_2 \sim Q_1$.

of curve P over Q; hence $A(P_{\$_1})$, is the area under price curve $P_{\$_1}$, from Q = 0 to Q_1. Similarly, $A(P_{S_1})$, is the area under supply curve P_{S_1}. Hence, the change in consumer, producer, and total surplus (Case 2 minus Case 1), can be written as:

$$\Delta S_C = \{A(P_{D_2}) - A(P_{\$_2})\} - \{A(P_{D_1}) - A(P_{\$_1})\} = A(P_{\$_1}) - A(P_{\$_2}) + \text{correction}$$

$$\Delta S_P = \{A(P_{\$_2}) - A(P_{S_2})\} - \{A(P_{\$_1}) - A(P_{S_1})\} = \{A(P_{\$_2}) - A(P_{\$_1})\} + \{A(P_{S_1}) - A(P_{S_2})\}$$

$$\Delta S_N = \Delta S_P + \Delta S_C = A(P_{S_1}) - A(P_{S_2}) + \text{correction}$$

where:

ΔS_C = change in consumer surplus

ΔS_P = change in producer surplus

ΔS_N = change in total surplus = net benefits

correction = $\{Q_2 - Q_1\} \bullet \{\hat{P}_1 + \hat{P}_2\}/2$

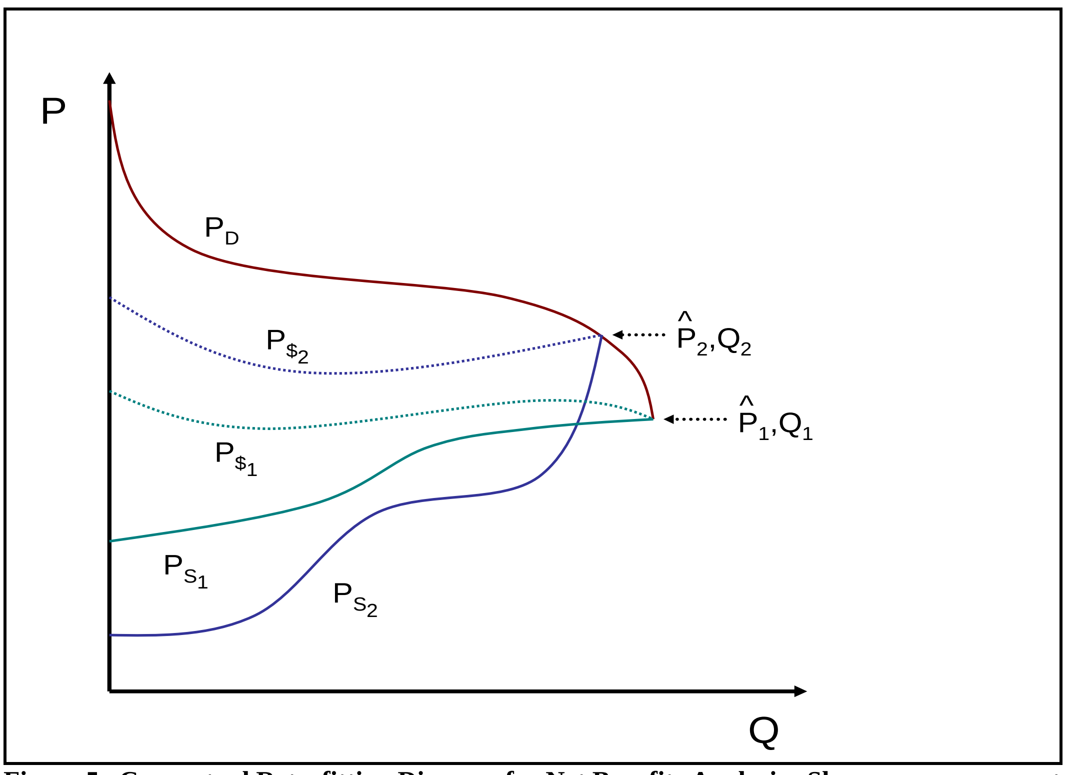

Figure 5. Conceptual Retrofitting Diagram for Net Benefits Analysis. Shown are components of net benefits analysis in a pairwise comparison of a test case (Supply Curve 2) against a base case (Supply Curve 1) with common demand curve. For generality, "price" curves are included since the average price is generally not equivalent to the marginal price. The hypothetical case presented here illustrates how total surplus could increase in spite of an increase in consumer prices.

According to the above, the only information needed with respect to the demand curve is in connection with the correction factor, which requires the marginal prices in each case and the assumption of linearity between the two cases. With respect to the supply curves and price curves, only the integrals under the curves are required. These statistics of the supply and price curves are effectively already tracked and reported in NEMS since they are readily derived from standard output metrics. Explicit knowledge of demand, supply, and price curves is therefore not required.

We associate the area under a price curve with total consumer expenditures, which is used to define the reported average price to all consumers (*Table 3, Energy Prices by Sector and Source)*:

$A(P_{\$_1}) = \overline{P_{\$_1}} \bullet Q_1$

$A(P_{\$_2}) = \overline{P_{\$_2}} \bullet Q_2$

Similarly, we associate the area under a supply curve with total costs to producers, which is tracked internally in NEMS and reported in a standard output table (*Table 116, Total Resource Costs – Electric Sector*).

$A(P_{S_1}) = C_1$

$A(P_{S_2}) = C_2$

Making these substitutions, we get to the basic methodology employed in this study (i.e. for pairwise comparisons under the assumption of a common demand curve):

$\Delta S_C = \{ \overline{P_{\$_1}} \bullet Q_1 - \overline{P_{\$_2}} \bullet Q_2\} + \text{correction} = \Delta\{\text{expenditures}\} + \text{correction}$

$\Delta S_P = \{ \overline{P_{\$_2}} \bullet Q_2 - \overline{P_{\$_1}} \bullet Q_1\} + \{C_1 - C_2\} = \Delta\{\text{revenue}\} - \Delta\{\text{costs}\}$

$\Delta S_N = C_1 - C_2 + \text{correction} = - \Delta\{\text{costs}\} + \text{correction}$

where:

$\overline{P_{\$_1}}$, $\overline{P_{\$_2}}$ = average price to consumers in Case 1, Case 2 (*Table 3)*

C_1 , C_2 = total costs of production in Case 1, Case 2 (*Table 116)*

An important caveat in using *Table 116* as the source for C_1 and C_2 is that fuel expenses in *Table 116* are based on "delivered prices" for fuels, which include the cost of carbon (carbon content multiplied by carbon value). To account for the net costs of capture and sequestration, fuel expenses must be adjusted by subtracting the embedded cost of carbon in the various fuels consumed and adding back the emission allowance expenses in *Table 117*. Embedded carbon expenses, significant for coal and natural gas, are estimated by multiplying the fuel consumption values in *Table 2* by carbon content[7] and carbon values in *Table 117*.

Estimated Net Benefits for Retrofitting and Repowering

To put the magnitude of net benefits observed in this work into context, cumulative savings in net production costs are relatively small in comparison to cumulative producer revenue (consumer expenditure), as shown in Figures 6 and 7. Savings are consistently positive in both the retrofitting and repowering studies, but in both cases the trend over time is suggestive of a breakeven process, consistent with observed penetration trends which showed retrofitting or repowering to require carbon emission allowance prices of at least 30 – 45 $/ mTCO$_2$e. In both studies, cumulative savings in net production costs tend to decline toward the breakeven point (zero) near the end of the forecast, perhaps a reflection that the ECP submodule minimizes the cumulative costs of production over a financial planning horizon of 20 years.

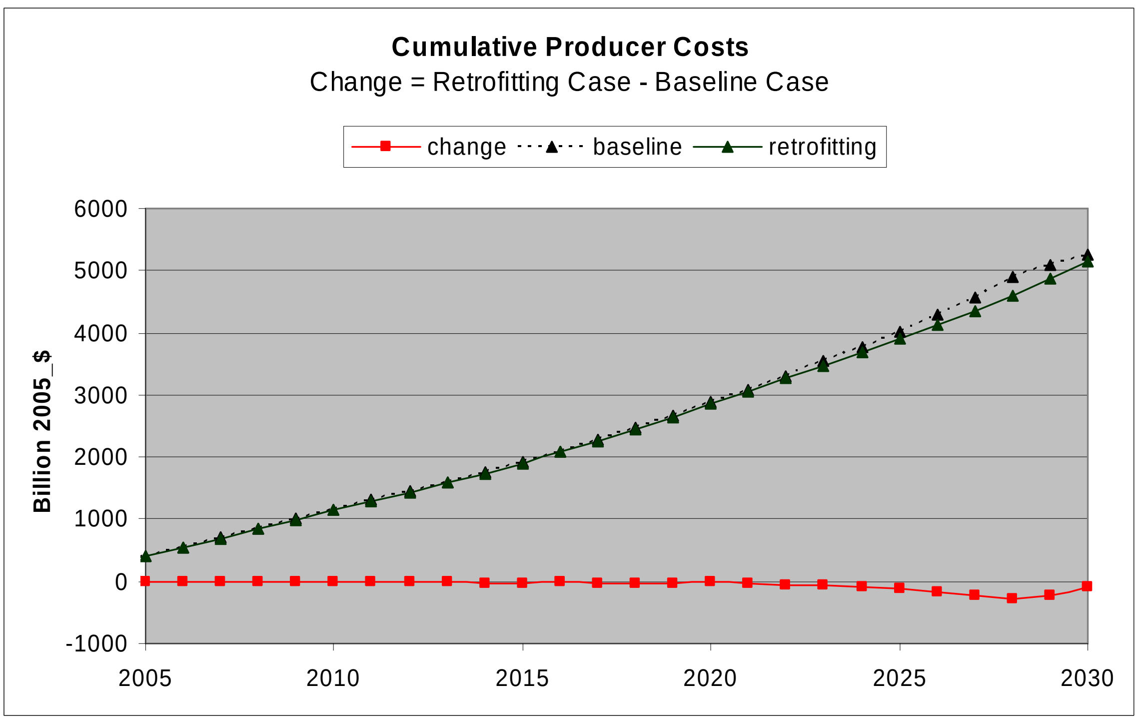

Figure 6. Cumulative Change in Producer Costs with Retrofitting at 45 $/mTCO$_2$e. Cumulative changes in costs are always negative, but eventually approach the breakeven point (zero) at 2030, consistent with the breakeven nature of retrofitting at 30 - 45 $/mTCO$_2$e, below which retrofits are not made.

[7] Average factors are used for coal, natural gas, and distillate carbon content; 0.103, 0.06, and 0.08 mTCO$_2$e/MMBtu, respectively.

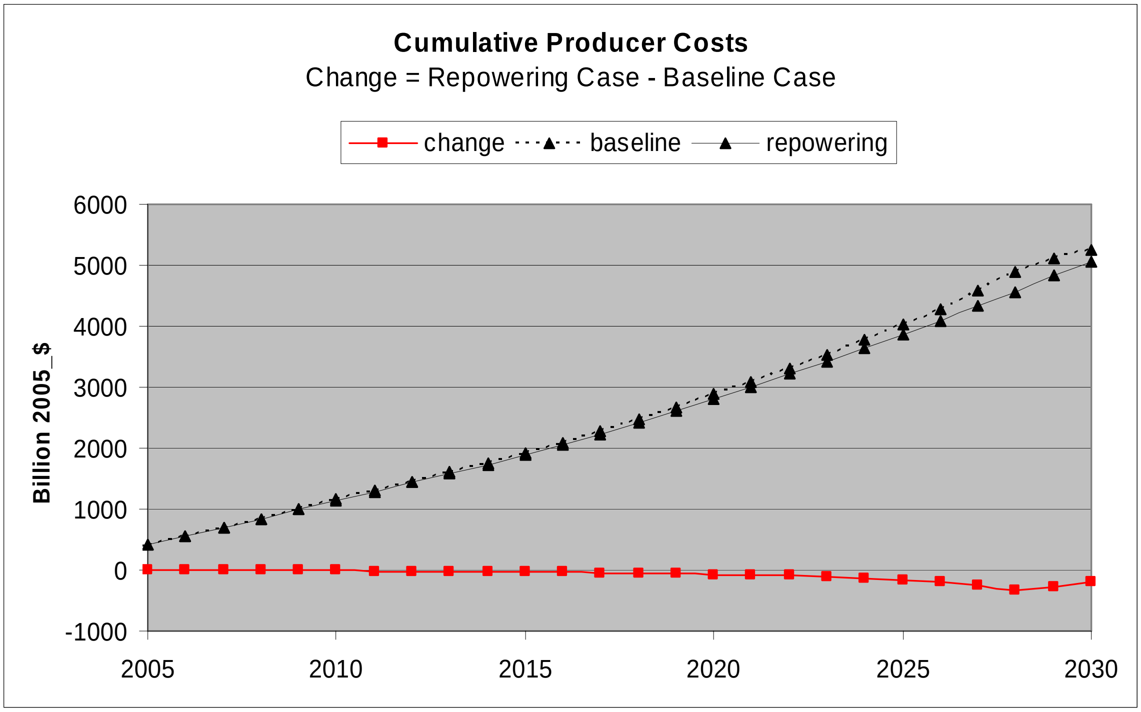

Figure 7. Cumulative Change in Producer Costs with Repowering at 45 \$/mTCO$_2$e. The steady decrease in costs of production reflects the steady penetration pattern observed in the repowering study. As in the retrofitting study, repowering is largely a breakeven option at 45 \$/mTCO$_2$e.

Another perspective on the magnitude of net benefits observed in this work is provided by the present value ratio, a commonly used ranking criterion for comparing alternative investments. A suitably simple measure of present value ratio is the cumulative net benefits of retrofitting or repowering divided by cumulative investment in retrofitting or repowering[8]. Retrofitting 100 GW of capacity at 45 \$/mTCO$_2$e required a cumulative investment of about \$100 billion. Hence, a present value ratio of about 1 is indicated for the net change in cumulative producer costs (net benefits) shown in Figure 6. Similarly, repowering 105 GW of capacity at 45 \$/mTCO$_2$e required a cumulative investment of about \$120 billion, corresponding to a present value ratio of about 1.5 for the net benefits shown in Figure 7. Hence, net benefits observed in this work are modest relative to overall producer costs or consumer expenditures for electricity, but relative to the investments in retrofitting or repowering, they are not insignificant.

Components of producer surplus in the two studies are summarized in Figures 8 and 9. The trends are similar with the exception that producer revenue (consumer expenditure) tends to be flat in the repowering study, but significantly increases in the retrofitting study. Figures 10 and 11 show a shift in the split of net benefits to favor producers over consumers in both studies. In the repowering study, net benefits are largely captured by producers, with essentially neither a gain nor a loss to consumers. Net benefits are largely captured by producers in the retrofitting study as well, but there is also a significant transfer of surplus from consumers to producers related to the increase in average consumer prices.

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[8] This simple definition is an estimate since the investment variable for calculation of present value ratio is formally defined as net investment inclusive of other investments (new capacity) before positive cumulative cash flow.

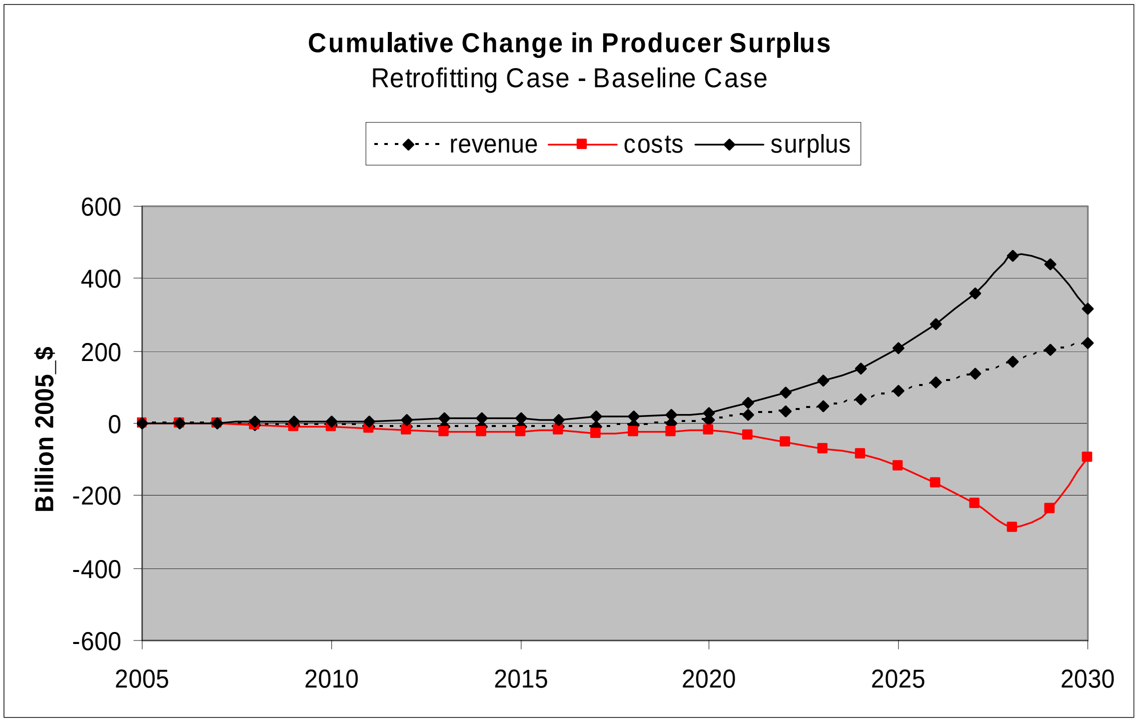

Figure 8. Cumulative Change in Producer Surplus with Retrofitting at 45 $/mTCO$_2$e. The trendline for production costs combines with a steady increase in revenue resulting in an increase in producer surplus (the peaking after 2028 may be an end-of-simulation artifact).

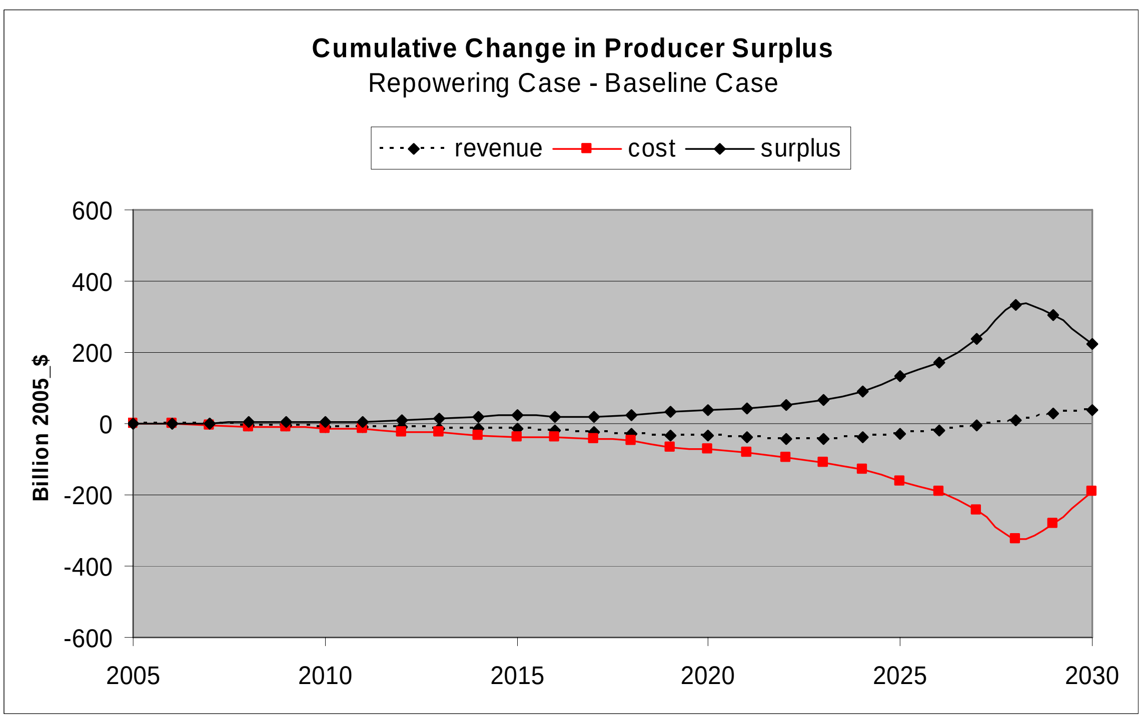

Figure 9. Cumulative Change in Producer Surplus with Repowering at 45 $/mTCO$_2$e. The neutral trendline for revenue differs from that in the retrofitting case, possibly due to the significant capacity deratings associated with retrofitting.

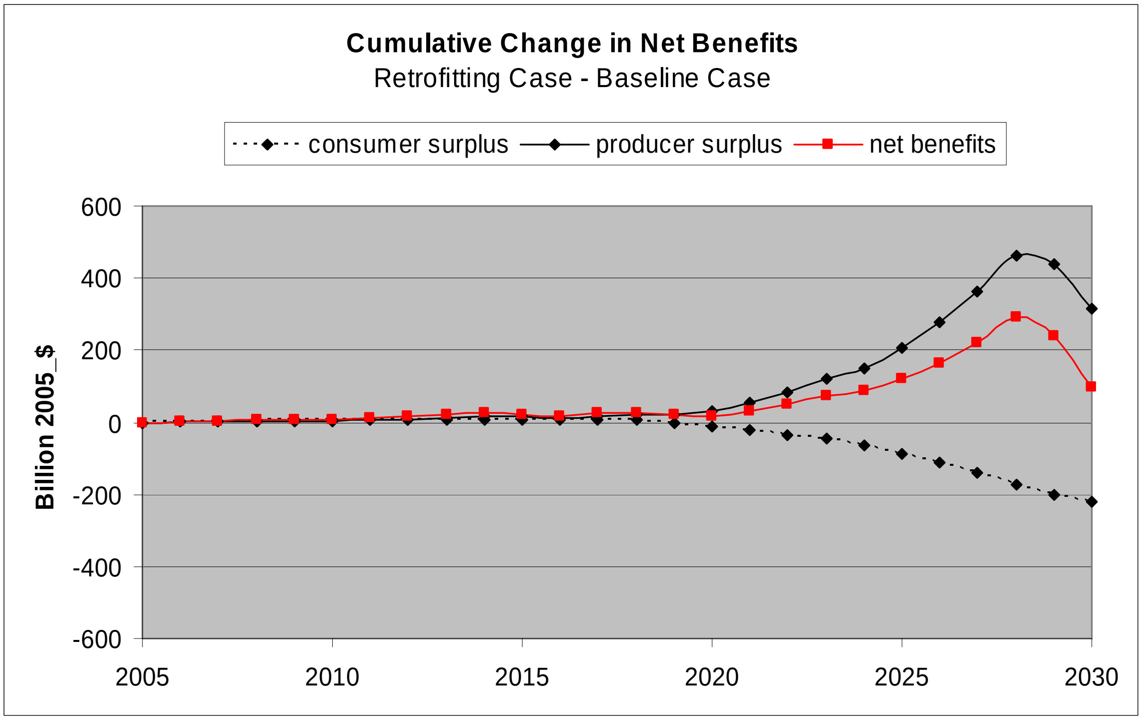

Figure 10. Cumulative Change in Net Benefits with Retrofitting at 45 $/mTCO$_2$e. A modest increase in net benefits (change in total surplus) occurs in the retrofitting study, by coincidence about one half that in the repowering study. There also occurs a shift of surplus from consumers to producers due to shifts in pricing, possibly related to capacity deratings.

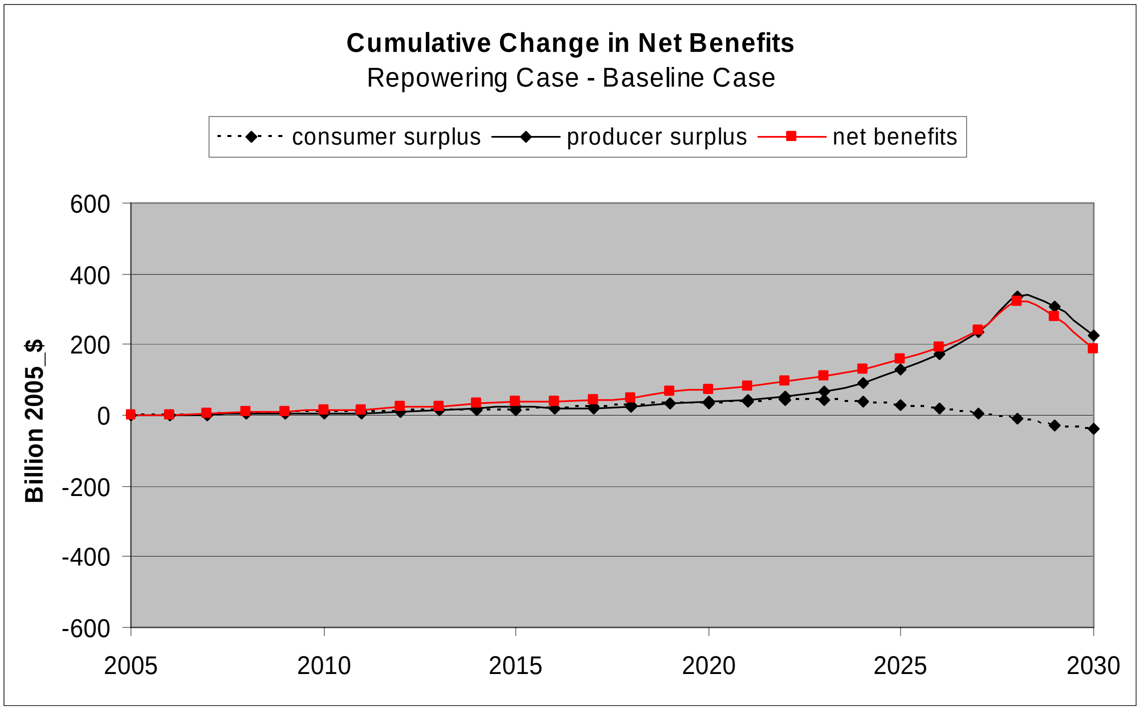

Figure 11. Cumulative Change in Net Benefits with Repowering at 45 $/mTCO$_2$e. As in the retrofitting study, a modest increase in net benefits (total surplus) occurs that is largely captured by producers rather than consumers, but the net impact on consumer surplus (expenditures) is much smaller.

Conclusions and Recommendations

Since cumulative net benefits are not persistently trending negative, modeled decisions or coding inconsistencies are not necessarily evident in either the retrofitting or repowering studies. Coding inconsistencies were identified, however, and revisions were developed to eliminate these as factors, but need to be implemented and tested before the impact of these inconsistencies can be fully understood.

Cumulative net benefits were consistently positive in both the retrofitting and repowering studies. In both cases, the split of net benefits undergoes a shift in favor of producer surplus over consumer surplus. The accentuation of this behavior in the retrofitting study may reflect the large capacity derating factor that was used for the baseline process in that study (about 30 percent deratings for 90 percent capture of CO_2 using an amine process). Hence, we could speculate the shifting to be a result of retrofitting or repowering high heat rate plants which are otherwise dispatched mostly for peaking.

The accentuation of adverse effects in the retrofitting study may also reflect the earlier and more rapid penetration of retrofitting, which effectively precludes subsequent decisions that might be more cost effective in the longer term. Hence, the limited planning horizon of the ECP submodule could be emulating important effects of imperfect decision making in regard to retrofitting or repowering as responses to possible climate change policies.

The observed trend in consumer prices with penetration of retrofitting or repowering would appear to be at least in part a net benefits phenomenon. Because of the shift in favor of producer versus consumer surplus, net benefits analysis may be required to use electricity price as a benefit metric in the analysis of R&D programs.

Appendix

ECP Submodule and Retrofit Submodule Interface

Two apparent coding inconsistencies were identified, both involving coefficients in the objective function that reflect the tradeoff in variable operation and maintenance (O&M) costs (including fuel costs and carbon fees) with retrofitting or repowering a given plant. Both inconsistencies are such that net O&M savings are probably overstated in the ECP submodule, which could then over-select plants which would otherwise be retired or maintained in status quo. When suboptimal selections are then passed to the EFD submodule, the effect could be to increase prices.

<u>Coefficients for Netting-Out Plant Level (Coal Supergroup) Tradeoffs from Aggregated ECP Group Tradeoffs</u>

The first coding inconsistency relates to how tradeoffs, at the plant level, are represented through the ECP submodule formulation based on aggregated plant groups. Corrections to the coefficients for the following row-column intersections are proposed, where row and column names are from the source code of the ECP submodule (subroutine UECP.F) as used for the AEO2007.[9,10] These corrections would be added in the section of subroutine EP$COAL where retrofit costs are added to each coal supergroup.

Row: UPOBJ
Column: GRP_CD(CGRP) // COAL // CFG

$$F\_1 = CF_t \{vom_f + \delta vom - VOM_t \bullet (1 - d)\} - CF_f \{vom_f - VOM_f\}$$

Row: 'F' // UPRGCD(FLRG) // UPLNTCD(ECPt_TO) // "SXX" // UPYRCD(IYR)
Column: GRP_CD(CGRP) // COAL // CFG

$$F\_2 = CF_t \{(hr_f \bullet p - HR_t)(1 - d)\} - CF_f \{hr_f - HR_f\}$$

Row: 'EUCARXX' // UPYRCD(IYR)
Column: GRP_CD(CGRP) // COAL // CFG

$$F\_3 = CF_t \{(hr_f \bullet p - HR_t)(1 - d)\} \bullet e_t - CF_f \{hr_f - HR_f\} \bullet e_f$$

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[9] Column name consists of variables defining the amount of capacity retrofitted for each coal supergroup. Row names designate the ECP submodule objective function, fuel consumption, and carbon fee. Variable operation and maintenance (VOM) cost effects are added directly to UPOBJ; fuel consumption and carbon fee effects are added indirectly through their respective free rows.

[10] See ftp://eia.doe.gov/pub/oiaf/ for source code; http://www.eia.doe.gov/oiaf/forecasting.html for related documenatation.

where:

F_1 = factor to net-out plant level variable-operating-cost effects from the ECP group average; added incrementally to existing terms for the annual fixed costs of retrofitting (including capital recovery); MM$/GW-year.

F_2 = factor to net-out plant level fuel consumption effects from the ECP group average; replaces the existing term in its entirety; MMBtu/GW-year.

F_3 = newly defined factor to net-out plant level carbon emission effects from the ECP group average (missing factor in existing code); $mTCO_2$/GW-year.

CF = annual average capacity factor for ECP group • (8,760/1000), hours/year.

hr, HR = heat rate of coal supergroup, ECP group; Btu/kWh.

vom, VOM = variable O&M of coal supergroup, ECP group; $/kWh.

d = capacity loss (derating) factor of retrofitting.

p = heat rate penalty of retrofitting.

δvom = incremental VOM of retrofitting coal supergroup plant, $/kWh.

e = x • (1 – r) = carbon emission rate; mTCO2e/MMBtu.

x = fuel carbon content, $mTCO_2e$/MMBtu.

r = fraction of fuel carbon captured and sequestered by retrofitting.

subscript f, t = group retrofitted from, group retrofitted to.

Construct for Converting Variable O&M into an Effective Annual Fixed O&M

The second coding inconsistency, also in subroutine EP$COAL, relates to an effective annualization of all variable O&M costs (including fuel costs and carbon fees) for the existing plant, added to fixed O&M for each coal supergroup plant before retrofitting:

FOM = CLSG_FOM(IYR,I_CLSG) + CLSG_VADJ(IYR,I_CLSG)

This would appear to double count variable O&M costs since these costs necessarily are accounted for in the ECP dispatch model through the capacity balance equation. Hence, the above usage of CLSG_VADJ would be discontinued.