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Capital constraints and the effectiveness of environmental policy

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Capital constraints and the effectiveness of environmental policy

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Abstract

This paper presents a framework to quantify the vintage structure of a capital stock, its relationships to material, energy use and carbon emissions, and impacts of technology investment on vintage structure and production. In our analysis we specify vintage classes by their age-specific retirement rates, material and energy intensities as well as fuel mix requirements. We further capture input substitution possibilities, embodied and disembodied technological change, and reflect impacts of learning and path dependency on industry performance. The framework is illustrated with a dynamic computer model of the US pulp and paper industry that captures regional differences in the structure of the industry's capital stock, investment behaviors and technological change, energy and material use and carbon emissions. Results demonstrate notable regional differences in industrial change and indicate the potential direct and indirect benefits and costs of using a price driven strategy to alter energy, material and carbon intensities.

Key Words

Capital vintage, environmental policy, carbon emissions, energy efficiency, technology lock-in, pulp and paper, technology change.

Introduction

Understanding the factors that influence the dynamics of industrial systems – their use of inputs and quantity and composition of outputs – is a fundamental prerequisite to properly anticipating impacts of energy and environmental policies on industrial energy use and greenhouse gas emissions. For example, most mature capital-intensive industries such as the metals production, the chemical industry, or pulp and paper manufacturing use capital stocks with large capacities and long service lives. Typically, investment is lumpy and occurs at irregular intervals, thus causing differences between the efficiency of new and existing capital to become increasingly pronounced over time (Doms 1996, Doms and Dunne 1999). Changing input mix and efficiencies of installed capital is often difficult in these industries, which limits the leverage that policy may have on their environmental performance.

To date, environmental and economic policy analyses of industrial dynamics have only paid limited attention to the influence of the structure of the capital stock on industrial dynamics. For example, conventional analyses of the economic impact and effectiveness of climate change policies in most cases do not capture industrial dynamics and do not contain descriptions of past investment behavior or future technology potential (a notable exception is the AMIGA model (Hanson and Laitner 2004)). Technology enters these models in the form of substitutable and homogenous inputs – including a homogenous and perfectly malleable capital stock. Given the *a priori* assumption of market efficiency and optimal choice of inputs, imposing policy interventions in these models is bound to raise cost of adjustment in industry. Furthermore, neglecting important attributes of the capital stock leads these models to prefer price-based policy instruments over other forms of intervention (DeCanio 2004, Jacoby and Wing 1999).

Recent empirical analyses suggest that capital vintage effects are important to understanding opportunities and constraints for energy and environmental policy in mature industries. For example, research by Gray and Shadbegian (2001) and Nystrom (2001) on the US and Swedish paper industry respectively, and research by Ruth and Amato (2003) and Worrell and Biermans (2005) on the US steel industry demonstrate significant capital vintage effects and show that investment patterns in most US industries are indeed "lumpy". The more disaggregate the study the lumpier the investment seems to be (Lempert et al. 2002, Doms and Dunne 1999).

Recognizing the role that capital vintage effects play in constraining industrial change and the effectiveness of energy and environmental policy, early efforts to capture the heterogeneity of the capital stock (Johansen 1959, Kaldor and Mirrlees 1962) have been extended and applied to analyze energy flows in industry (Ruth et al. 2004, Ruth and Amato 2003, Davidsdottir and Ruth 2004, 2005, and Jacobsen 2000). Capital vintage models distinguish between the impact of replacement and expansion investment on changes in input efficiency and enable an explicit assessment of the impact of capital vintage dynamics on energy, material and waste flows.

This paper presents an expansion of theoretical vintage models developed by Meijer (1994), Ruth et al. (2004) and Davidsdottir and Ruth (2004). It heeds the call by leading international industry experts for less aggregated analytical economic modeling and increased presence of engineering-economic analysis in the context of climate change policies in order to overcome the shortfalls of both and to provide better insights for policy making (Dowd and Newmann 1999, ACEEE 2003). Specifically, we present a dynamic modeling framework that enables the integration of physical and economic information, where capital dynamics and energy and material flows are explicitly accounted for. The paper explores the importance of incorporating capital vintage dynamics when assessing industrial change, in particular focusing on the relative importance of embodied and disembodied technological change and learning-by-doing in addition to the impact of capital inertia on the effectiveness of environmental policies. The paper also reveals substantial co-benefits and costs of price driven policy options that would not be realized in a conventional single-medium economic model of environmental policies.

The remainder of this article is organized as follows: We first review the economic drivers of industrial change in the context of capital vintage dynamics. Then we describe the implementation of the modeling framework in a regional analysis of the US pulp and paper industry, beginning with a description of the system and system boundaries, followed by a relatively detailed description of the model itself. We chose the US pulp and paper industry because it is one of the most capital-intensive industries in the United States, is fairly mature and has a very long-lived service life of capital (Davidsdottir and Ruth 2004). The third section of the paper presents the results of four scenarios focusing on implications for energy, material and climate change policy of observed capital vintage dynamics. The article concludes with a summary of our findings and a discussion of the relevance of the approach and findings for the design of climate change policies.

Industrial Dynamics and Impact on Input Efficiency

Change in an industry often manifests itself as a change in product volume, energy and material use, and emissions. Change in an industry's average input intensity of energy and material flows is commonly decomposed into three separate components: one resulting from technological change[1], one from structural change and one from input substitution (Farla et al. 1997), whereas the scale of material and energy flows is a function of input intensity, output structure, which consists of different products, and output volume (Levine 2003). Economic and engineering factors then influence each of those components which overall capture industrial dynamics.

Capital Vintage Dynamics and Technological Change

The capital stock[2] of each industrial system is built of numerous age classes (vintages) each of which has its own characteristics. Vintage specific features include the rate of depreciation, input efficiency and substitution possibilities. For instance, an older vintage is likely to require a larger amount of input materials to produce the same amount of physical output, when compared to a new vintage (De Beer 1998, Lempert et al. 2002).

An industrial system evolves through an expansion of the capital stock or through the gradual replacement of old, worn out or retired structures. The expansion of a capital

[1] Technological change is defined as a reduction in the use of an input, holding other inputs and output constant. Structural change can of course change the input use, but at the same time will change the output mix.

[2] In this paper we distinguish between physical capital and financial assets, and only focus on physical capital such as machinery and buildings.

stock will, by definition, increase the use of input materials and slightly improve material and energy efficiency assuming the industry invests in more efficient capital. Replacement investment, which includes retrofits, more extensively increases energy and material efficiency, and keeps constant or reduces total use of material and energy inputs. Thus, the investment process incrementally changes the flows of material and energy into and out of the system. In this context, a distinction is typically made between embodied technological change, which influences new capital vintages, and disembodied change, which influences the efficiency of already installed capital (Solow 1957, Meijer 1994, Berndt et al 1993, Davidsdottir 2004).

Embodied technological change occurs as technology becomes embedded within the capital stock due to either expansion or replacement investment. Embodied change is influenced by learning which has an impact on the efficiency of new capital, and in industrial systems is highly path dependent (Arthur 1994, Unruh 2000, Kuper and Soest 2003). Path dependency is the result of mature industries investing in similar technologies through time and combined with long service life of capital and thus substantial capital inertia, fostering incremental rather than radical changes in technology. Choices made early on in the development of an industry gradually locks-in a technological rigidity efining the future technology trajectory as a function of the structure of the existing capital stock. Evidence of substantial embodiment has been confirmed, for example, by Sakellaris and Wilson (2004), which find that each vintage is about 12 percent more productive on average than average older equipment and that embodied technological change accounts for 2/3 of all output growth in the United States. Greenwood et al. (1997) demonstrate that 58 percent output growth in the US between 1954 and 1990 was due to embodied technological change. Such significant investment driven technological change indicates the importance of investment driven policy when reducing energy or carbon intensity. It also highlights the importance of not adopting measures that will reduce the rate of embodied change.

Disembodied technological change only influences “older” vintages and is a change in input efficiency of the already installed capital stock. It occurs not as a result of retrofits or replacement investment, but as a function of regular minor maintenance (Lempert et al. 2002) and of low- or no-cost operational changes (Ross 1991). Such changes can be in the form of improved housekeeping practices and typically do not require a substantial investment in fixed capital structures. Examples are improved insulation and the use of more energy efficient light bulbs. Learning-by-doing plays a central role in disembodied change as enterprises gain experience in operating equipment, and thus gain efficiency after capital is installed (Meijer 1994, Davidsdottir 2002, Ruth et al. 2004, Davidsdottir and Ruth 2004, 2005). Theoretically, recently installed capital equipment can be more efficient than it was when it had just been installed (Meijer 1994, Pakes and Griliches 1984, Lempert et al 2002). According to Sakellaris and Wilson (2004), disembodied technological change accounted for about 1/3 of all productivity increase in the United States between 1972 and 1996.

Structural Change and Input Substitution in the Context of Capital Dynamics

Structural change of an industry is defined as a change in the output mix and is driven by demand and other factors in an industry’s economic environment, and is constrained by the vintage structure of the capital stock. An example of structural change in the paper industry is a shift from newsprint towards printing and writing papers. Because fiber and energy requirements differ substantially for those two products – they are produced using different pulping processes – such a shift would influence both energy and material intensity as well as the character of those flows (Ruth and Harrington 1998, Davidsdottir 2004, Energetics 1990).

Input flows also change in response to direct input substitution. Three main variants of substitution are frequently distinguished. Substitution may be "putty-putty" – it is equally feasible to substitute inputs within both new and old vintages; "putty-clay" – substitution is only feasible for new vintages; or "clay-clay" – substitution is not possible for either new nor old vintages. In disaggregated industrial systems analysis it is most common to use clay-clay specifications, as relationships among broad input groups, such as materials, energy labor and capital, are relatively fixed for a given technology.

Case Study

General System Description

The organizational structure of the US pulp and paper industry (NAICS code 322) can broadly be divided into three tiers: pulp production, paper and paperboard production and finished products production (Smith 1996). The industry is regionally heterogenous, mature, vertically integrated and adequately represented by a competitive market structure (Davidsdottir 2004).

Over the last 30 years the average annual growth in total paper production in the United States exceeded 2 percent per year, but has declined in the early 2000's. Regional growth rates vary widely. Currently, total production is slowly shifting towards South Central Regions and generally away from northern regions such as New England and the Mid Atlantic. Product mix is also nationally heterogeneous.

Material inputs primarily consist of waste or virgin fibers with a wastefiber-utilization rate (WUR) averaging 35 percent, yet regionally varying from 22 – 54 percent (see Table 1). Wastepaper pulping requires less total energy per ton of pulp than pulping processes that use virgin fibers such as kraft pulping. In contrast to kraft pulping of virgin wood, wastepaper pulping does not provide wood-wastes or dissolving chemicals for the self-generation of energy and in total has higher purchased energy intensity than kraft pulping.

Fuel intensity and fuel mix also are regionally heterogenous. The industry on average self-generates over 55 percent of its energy needs, regionally varies from 30 to 63 percent (Table 1). Table 1 illustrates that production in regions that rely on virgin fibers on average are more energy intensive but rely to a larger extent on self-generated energy.

The industry is one of the most capital-intensive industries in the United States with capacity-utilization-rates averaging over 90 percent. Low profit margins and high capital intensity necessitate the industry to operate at almost full capacity, and any halt to production, for example, to update antiquated equipment, comes at a high economic cost of foregone production. Hence, any updates in energy efficiency are often realized as side-results to changes in production capabilities and are highly path dependent. As may be expected, technological change has been incremental (rather than radical). As a result of this path dependent behavior, the immense capital intensity of this industry coupled with low rates of capital turnover (equipment as old as 100 years or more is still in use within the industry[3]), has resulted in significant capital inertia. Additional evidence of the industry's incremental change can be found in research by for example Herzog and Tester (1991) and Norberg-Bohm and Rossi (1998).

System Boundaries

For the purposes of this study the industrial system is disaggregated into 8 US census regions (see Table 1), as defined by the US Census Bureau. Regional disaggregation enables us to reflect differences in behavioral characteristics and the regional heterogeneity enables us to more accurately reflect interactions between the dynamics of capital vintages and energy and material flows.

Production within each region is disaggregated into four paper products (newsprint, tissue, printing and writing, packaging and industrial paper), and four paperboard products (kraft paperboard, bleached kraft paperboard, semichemical paperboard and recycled paperboard). The model captures the vintage structure of the physical capital stock by region, annually, back to the year 1950. Because of a lack of sufficiently detailed data, capital installed before 1950 is aggregated and assumed to have uniform characteristics. The "evolution" of the capital stock is simulated by region-specific rates of expansion and replacement investment.

The model captures the regional flow of materials by type and process. Virgin materials flow from forestry operations to the pulp and paper making process and flow out of the system as wastepaper. The model captures the flow of domestically produced wastepaper and traces its fate – either into the industrial system again or into the solid waste stream. After wastepaper ends up in the solid waste stream, it is assumed either incinerated or put into landfills. Consequently, the model excludes the possibility of wastepaper exports, which in recent years have become significant.

The model distinguishes, within each region, six different fuel types that are purchased by the industry (natural gas, residual fuel oil, coal, electricity, and distillate fuel oil in addition to "others" that include steam and LPG) and traces the extent to which the industry self-generates energy. The latter is modeled as an aggregate of spent liquor, hogged fuels, bark and wastepaper. Combined Heat and Power (CHP) is not explicitly modeled, but is incorporated into future efficiency descriptions for chemical pulping as self-generated energy.

In summary, the model traces simultaneously, by region, the physical uses of energy and materials by type and relates their changes to changes in the regional structure of the capital stock and output levels/mix. Carbon dioxide from the burning of fossil fuels as well as methane and carbon dioxide emissions from paper decay in landfills are also captured. Energy and materials used in the transport of paper products to the market, in the collection of wastepaper and in the forestry sector are considered outside of system boundaries.

Model Structure

The model structure is based on five interacting modules. The modules are:

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[3] The paper industry is not alone in having a long-lifetime of capital. In the power industry over half of the power plants built before 1950 are still in operation (Lempert et al 2002).

- **A Production Module**, which simulates regional production levels/growth by product type that are limited by available production capacity and are estimated based on a reduced form production function (Kaltenberg and Buongiorno 1986) incorporating the gravity model (Haynes and Fotheringham 1983).
- **A Physical Capital Vintage Module**, which describes the size of each capital vintage and simulates changes in the size of existing vintages and the addition of new vintages as a function of replacement and expansion investment.
- **An Input Intensity Module,** which relates the input intensity of each input type by vintage, to the size of each vintage, giving the total intensity of the capital stock, and combined with the production module gives total use of each input type.
- **An Input Mix Module,** which simulates changes in the input mix, i.e. the switch between process fuels and from virgin to waste fibers**.**
- **A Greenhouse Gas Emissions Module,** which describes emissions of methane and carbon dioxide from landfilled paper using the EMCON methane generation model (EMCON 1982, NCASI 1999) using decay parameters derived from Peer et al (1993), methane generation capacity by paper type derived from Doorn and Barlaz (1995) and Augenstein (1992) and emissions from the use of process fuels by type and emissions due to paper incineration.

Each region-specific module is specified with non-linear differential equations. The complete set of simultaneous differential equations is solved at an annual time step. Parameter estimates for the respective equations are based on time-series analysis of 29 years of historical data (1970 – 1998), vintage-based capital analysis and engineering/physical information. Each econometric equation is subject to and must pass extensive diagnostic tests, such as for heteroscedasticity, serial correlation and unit roots.

Capital vintage module

The capital stock reflects annual physical investments, measured in short tons of productive capacity, made between 1950 and the present. An econometrically estimated vintage specific replacement rate is applied to each vintage. A vintage specific perpetual inventory model is then used to simulate changes in the vintage specific regional size of the capital stock (Jorgenson 1996) and is used to track changes in the size of the total capital stock. Equation 1, presents a conventional perpetual inventory model, which describes in discrete time the size of the regional end-of-period capital stock (K)[4].However, our implementation of the capital vintage module tracks each installed gross investment (I), which then subsequently declines over time as a function of vintage and time specific physical replacement rates (μ_τ) (equation 2). Thus each year a specific fraction of each vintage is removed.

$$K = I + K_{t-1} * (1 - \overline{\mu}) \qquad (1)$$

[4] Note that each parameter is region and time specific; region and time specific subscripts are suppressed to simplify notations.

$$K = I_\tau + \sum_{\tau=1}^{T-1} \left(I_{\tau,t-1} * (1-\mu_\tau) \right) \qquad \text{with } 0 \leq \mu_\tau \leq 1 \qquad (2)$$

The physical depreciation rate captures replacement and retirement, and τ represents the year of installation of each vintage. The size of each new capital vintage is given by gross new capital investment (I_τ).Gross new capital investment is a function of expansion investment (*EXP*) and replacement investment (*REPL*) (equation 2).

$$I_\tau = (EXP + REPL) \text{ with } \quad EXP = K - K_{t-1} \qquad (3)$$

Expansion investment is econometrically estimated as a function of changes in input prices (*p*), changes in output (*Q*) and changes in capacity utilization parameters (*Q/K*) (equation 4). According to Jorgenson (1996), a lag time exists between the time of the initiation of an expansion investment project, and the time by which the new physical capital has been installed. For the aggregate US paper industry this lag time has been estimated at 2.08 years (Jorgenson 1996) and is directly incorporated into equation 4.

$$EXP = f((p_{t-2} - p_{t-3}), (Q_{t-2} - Q_{t-3}), (Q_{t-3}/K_{t-3} - Q_{t-4}/K_{t-4})) \qquad (4)$$

Since REPL ≥ 0, and -K ≤ EXPI≤ + ∞, expansion investment (net investment) can theoretically be negative which would indicate a decline in the total size of the physical capital stock.

Regression results indicate that the only input whose price has a significant impact on expansion investment is the price of energy. In each region, the price of energy has a negative impact on the level of expansion investment, indicating that if energy prices increase we can expect the level of expansion investment to decline. Since improvements in energy efficiency are in most cases directly linked to updates and expansions in production, an increase in energy prices will thus simultaneously reduce the rate of energy saving embodied technological change that is derived from expansion investment. Lagged changes in capacity utilization have a significant impact on expansion investment, indicating that an increase in capacity utilization will facilitate an increase in expansion investment. However, an increase in lagged production levels has a negative impact on expansion investment, indicating that the level of expansion investment declines after expansion in investment and an increase in production levels occurred. This result is similar to findings by Doms and Dunne (1998), which reveal that investment is indeed lumpy, and after years of expansion, the level of expansion substantially declines.

Replacement investment by definition equals the proportion of gross investment that directly replaces retired and depreciated capital (equation 5).

$$REPL = \sum_{\tau=1}^{T-1} (I_\tau * \mu_\tau) \qquad (5)$$

Physical replacement rates are econometrically estimated using a Gompertz curve of total replacement rates, and are estimated as a function of age, but also influenced by input prices (p) (equation 6).

$$Total\mu_{\tau} = \frac{MaxTotal\mu}{EXP^{\alpha_0 * \exp^{\alpha_1 * age + \alpha_2 * p_j}}} \qquad \text{where } 0 \leq Total\mu_{\tau} \leq 1$$

(6)

When $Total\mu_{\tau}$ =1, then the entire vintage has been replaced by new capital. Time-series data on total physical retirement rates was created from annual data of productive capacity by region still in service (AF&PA various years). For example, if 100 units were installed in 1990 and in 2000 only 90 of those units were still productive, the total replacement rate in 2000 would be 10 percent, indicating a survival rate of 90 percent (Worrell and Biermans 2005). A sample of the actual data is provided in Figure 1 below.

INSERT FIGURE 1 HERE

We derive dynamic vintage specific replacement rates by differencing once the econometrically estimated total replacement curve based on age of capital. The econometric results indicate that the only economic parameter with significant impact on replacement rates is the price of energy. Increases in energy prices will shift the replacement curve outwards, facilitating a decline in replacement of young capital, but increasing the rate of replacement of older capital. Because the pulp and paper industry is heavily reliant on older capital, an increase in energy prices can thus be expected to increase the level of replacement investment.

Input Intensity – Technological Change

Total input use is a function of input intensity and the scale and mix of output. Input intensity is directly influenced by technological change and input substitution. Technological change is assessed as either embodied or disembodied.

First, we assess the input intensity of each new capital vintage which combined with gross investment constitutes embodied technological change. The input intensity of each new vintage depends on the regional relative input intensity RII^{j}) by input j, of new to old capital (EIA 2002) and the weighted average embodied intensity of the existing capital stock ($WAIE^{j}_{t-1}$) (equation 8). The vintage and input specific *RII* is a function of region and process specific output mix and process specific relative input intensities (*RIIS*), weighted by the contributing share of process i to total output (*Q*) (equation 7). $WAIE^{j}_{t-1}$ is a function of average intensity of all vintages weighted by the vintage specific fractional share in total production (equation 9). The use of REI's as estimated by the EIA assumes that firms invest in best available technologies when expanding/replacing the capital stock, which has been confirmed by empirical research by Sakellaris and Wilson (2004). Of course a change in firm preferences, such as due to increased awareness of climate change policies, which could reduce hurdle rates for new more efficient technologies would increase the "efficiency gap" between new and existing technologies and result in increased efficiency targeted investment and thus embodied technological change. This approach in addition allows for the incorporation of both path dependency and learning into simulations of future directions of embodied technological change. That is, if the industry invests heavily in new capital, then new capital constitutes a larger influence on weighted average intensity, which accelerates efficiency improvements.

$$RII^j = \sum_{i=1}^{8} (RIIS^i * (Q \Big/ \sum_{i=1}^{8} Q^i)) \quad (7)$$

$$EIE_\tau^j = RII^j * WAIE_{t-1}^j \quad (8)$$

$$WAIE^j = \sum_{\tau=1}^{T-1} (EIE_\tau^j \frac{(I_\tau * \frac{Q}{K})}{Q}) \quad (9)$$

The combination of accounting for a heterogenous capital stock in terms of size by vintage and vintage specific efficiencies greatly improves the ability of our model to simulate changes, both desired and possible, in input intensity and thus energy and material flows. It facilitates the incorporation of both path dependency and learning on industry behavior, which then combined with process specific engineering based estimates of future technology potentials enables more appropriate modeling of new capital, which is likely to produce a significant different outcome than results, which depend on purely historical time-series. In addition, the modeling of a disaggregated capital stock, both by age and region, and its associated vintage and region specific input intensities enables, for example, the modeling of policies that modify vintage-specific retirement rates on changes in total energy or material use and thus waste flows. Given the lumpiness of capital investment and the dominance of old capital in the industry, the disaggregation by age and region this disaggregated modeling approach is bound to give different and more realistic results than an approach that assumes a homogenous capital stock, and is based on average input intensities.

After new capital is installed and its vintage specific input intensity is embodied into the capital stock, vintage specific input intensity is “locked in “ for each installed vintage , though changes can occur as a result of disembodied changes or retrofits and replacements. In such cases, retrofitted capital moves to the front end of the vintage structure, and its intensity is reevaluated as new capital.

Disembodied technological change according to definition is assumed not to be capital intensive, but is influenced by for example by learning by doing and input prices (Meijer 1994, Doms 1996, Sakellaris and Wilson 2004). Because learning how to optimally use machinery takes time, newly installed machines may possibly become relatively more productive than newer machines (Doms 1996, Lempert et al 2002). This phenomenon has been confirmed in studies by e.g. Doms (1996) and Pakes and Griliches (1984) and Meijer 1994. We assess disembodied changes in the physical input efficiency of the existing capital stock (AE^{old}) as a function of cumulative production ($CumulativeQ_{t-1}$) and input prices (p^j) (equation 10), A and α are econometrically estimated constants. Disembodiment is assumed to affect each vintage in the existing capital stock equally[5] and the rate of disembodied change is measured using equations 10 and 11.

$$AE^{old} = A * (CumulativeQ_{t-1})^{-\alpha 1} * (p^j)^{-\alpha 2} \qquad (10)$$

$$\Delta AE = AE_t^{old} - AE_{t-1}^{old} \qquad (11)$$

To create the data-series on disembodied intensity change, we assess aggregate energy intensity over time, as the average input intensity of existing capital, corrected for the addition of new, more efficient capital. Econometric estimates of equation 10 indicate that both an increase in energy prices and cumulative production reduces energy intensity. Combining both embodied and disembodied technological change gives vintage and input specific intensity (IE_τ) of the productive capital stock (equation 12). Total input use by type j (TI) is measured as a function of vintage specific intensity and production levels from that specific vintage (equation 13).

$$IE_\tau^j = EIE_\tau^j * \left(1 + \frac{\sum_{\tau=1}^{T-1} \Delta AE^{old}}{AE_{t-1}^{old}}\right) \qquad (12)$$

$$TI^j = \sum_{\tau=1}^{T} \left(IE_\tau^j * \left(I_\tau * \left(\frac{Q}{K}\right)\right)\right) \qquad (13)$$

Input Substitution

Substitution between energy types is simulated as the simultaneous change in non-quality adjusted fractional shares of all fuels as a function of changes in energy prices, output mix and wastepaper utilization. Econometric results indicate that an increase in wastepaper utilization does reduce the rate of increase in the share of self-generated fuels. Own price elasticities are everywhere negative and significant. Total share of each fuel is then estimated from the simulated fuel shares and total energy use from equation 13.

The choice of fiber types is directly tied to the choice of specific pulping technologies. We use the Fisher and Pry technology substitution model (Fisher and Pry

[5] This assumption results from a lack of data to specify empirically changes in vintage specific ex-post input efficiencies. However, this assumption is clearly a simplification of reality where disembodiment is expected to show an inverted U-shaped impact on vintages, skewed to the right. The largest impact is expected to be on vintages between 3-7 years old (Meijer 1994). This has however, yet to be confirmed empirically.

1971) to assess the movement towards/or away from a maximum region specific wastefiber utilization rate, as a function of input prices, cumulative production and the enactment of recycling legislation. Total fiber use by type, is then assessed as a function of total pulp needs from equation 13, and fractional shares of either wastefiber or virgin fibers, corrected for shrinkage. To achieve mass-balance in the industrial system as a whole, waste-fibers are assumed to originate in one year old domestically produced paper only. Fifteen percent of non-recycled wastepaper is assumed incinerated and 85 percent is assumed landfilled.

Greenhouse Gas Emissions

The paper industry contributes both directly and indirectly to greenhouse gas emissions, mostly in the form of carbon dioxide (CO_2) and methane (CH_4). Because of potential trade-offs between methane and carbon emissions from this industry, and thus the existence of potential co-benefits or co-costs from climate change policies, we assess the following two carbon emissions metrics in this paper:

- Net Carbon Emissions: carbon emitted in the form of carbon dioxide from fossil fuel combustion, assuming self-generated fuels are carbon neutral.
- Gross Carbon Emissions: CO_2-equivalent emissions of carbon, from fossil fuel combustion, waste-paper incineration and decomposition of paper products in landfills using the EMCON methane generation model (EMCON 1982).

Results

To explore the dynamic behavior of this industry, the importance of technological change and the extent of capital inertia in addition to the effectiveness of price driven climate change policy we run four different simulation scenarios. In each scenario, the model is run from 2000 to the year 2020, using exogenously forecasted data of regional input prices and regional income, in addition to endogenous parameters as indicated in the description of the model. The scenarios are:

(1) A base case using the regional growth rate forecasted by the Bureau of Economic Analysis (BEA)
(2) A high growth case, based on regional rates that are 5 percent above region specific growth rates.
(3) A low growth case, based on regional growth rate that are 5 percent lower than the base growth rate.
(4) A simulated climate change policy, which constitutes of a $100 per ton of emitted carbon implemented in 2005 (a carbon tax[6]), combined with regional growth rates identical to the base case in addition to the high and low growth cases as in scenarios 2 and 3 above[7].

[6] It could be argued that a carbon tax is not a policy option that is on the table in the United States, however in a recent book edited by Morgenstern and Portney (2005), called "Energy and the Environment Policy Advice for the President, and published by RFF Press, Burtraw and Portney (chapter 3) argue for the enactment of a carbon tax. Also, several European countries have installed carbon taxes.

[7] Another alternative scenario that could have been run, was an investment incentive scenario. However since the motive of the analysis was to assess the impact of price driven scenarios, compared with business as usual we opted not to include such a scenario in this paper. However based on the results that follow it is likely that an investment drive scenario would have facilitated considerably faster decline in energy and

Growth Scenarios

The three growth cases reveal the following:

- Total energy intensity overall is declining in all regions, with the intensity of purchased fuels (or net carbon intensity) declining faster than the intensity of self-generated fuels due to the continued shift towards self-generated energy. This implies reduced reliance on purchased energy at the national level.
- When comparing changes in energy intensity across regions, it becomes apparent that energy intensity declines most rapidly in regions where production is expanding the fastest (that is in West North Central, East South Central and West South Central regions). This is because as growing regions expand their capital stock, they tend to invest in new more efficient capital reducing overall energy intensity as a result of embodiment. Also, the faster production volume grows, learning rates increase, which both accelerates the rate of embodied and disembodied technological change. The two alternative growth scenarios reinforce this observation. In the high growth scenario, the rate of both embodied and disembodied technological change increases, embodied due to larger gross investment volumes and investment learning, and disembodied due to the impact of learning by doing. Combined, this results in a more rapid decline in total energy intensity in all regions. In the low growth scenario, the decline in energy intensity occurs more slowly than in the high growth and the base scenarios due to slower speed of both embodied and disembodied technological change.
- In the base scenario, the contributing share of embodied technological change to overall change in energy intensity ranges between 78 percent (New England) to 84 percent in West and East South Central. Thus disembodied changes account for between 22 to 16 percent of total changes in energy intensity in the industry[8]. Because gross investment facilitates embodied technological change, and is more extensively affected by replacement investment, this result confirms the importance of environmental and energy policies that facilitate increased capital replacement and thus faster rates of capital turnover, in particular if the objective is to permanently alter energy, material or emission profiles of an industry.
- Similarly, net and gross carbon intensity decline over time (see Figures 2, 3 and 4). On the one hand, net carbon intensity declines faster than total energy intensity due to the continued shift to self-generated fuels and declines faster in high growth scenarios. As expected this continued shift occurs faster in regions dependent on the use of virgin fibers such as East South Central (Figure 3). On the other hand, gross carbon intensity declines more slowly than net carbon intensity due to built-up paper-waste in landfills that, due to the relatively slow decomposition of paper, continues emitting carbon in the form of methane long after the paper is landfilled (Figure 4). Because carbon from methane accounts for 53 percent of net carbon emissions, and the low growth scenario facilitates less production volume and thus less landfilled

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carbon intensity than the price driven scenario and possibly prevented the observed decline in the use of recycled materials.

[8] This result should be considered as an upper limit on the importance of embodied change because of the assumed behavior of always investing in more efficient capital. Empirical evidence confirms this assumption to be valid, but nevertheless it may overstate the movement in intensity due to embodiment.

paper, gross carbon intensity declines faster in the low growth scenario when compared to the high growth scenario (Figure 4).

- Simulation results indicate substantial regional differences in the regional *paths* of carbon emissions and carbon intensity and regional paths of energy use and energy intensity. Different regional developments and character of output and input mix, and thus WURs and the extension possibilities of self-generated energy can mostly explain this difference in addition to regional differences in the rate of technological change. This indicates the close relationship between energy and material flows, and how choices in use of materials and output type, influence technology trajectories for energy use and thus carbon emissions. Net carbon intensity is lower in regions that mostly rely on virgin fibers, and declines faster due to a continued shift to increased energy self-generation, which by definition is carbon neutral, and more rapid technological change due to higher investment and production levels.

INSERT FIGURE 2 HERE

INSERT FIGURE 3 HERE

INSERT FIGURE 4 HERE

An increase in the cost of carbon: climate change policy scenario

- Waste-fiber utilization rates (WUR) significantly decline in regions heavily reliant on virgin fibers, because as energy prices increase the industry shifts to processes that enable energy self-generation and at the same time rely on virgin fibers. WURs stay relatively constant in regions heavily reliant on waste-fibers because energy price elasticity of total paper production and categories that rely on recycled paper is similar in those regions.
- Expansion investment in all regions declines when compared to the base scenario. The investment that occurs appears to shift toward processes that are more energy intensive in total, but rely less on purchased energy and waste-fiber pulping.
- Replacement investment slightly increases in all regions, because replacement rates increase for older capital.
- Put together, those trends reduce both total energy and material use and at the same time reduce total energy intensity in all regions, when compared to the base scenario. The rate of decline in energy intensity due to technological change is a function of the relative movements in expansion and replacement investment (embodied change) and disembodied change. The rate of embodied technological change significantly slows down, and thus *embodied energy intensity* in 2010 and 2020 in all regions is higher than in the base scenario. This indicates that the decline in expansion investment, and the shift to investing in more energy intensive processes, outweighs the marginal increases in replacement investment. However, the rate of disembodied change increases substantially, in particular in regions where production volume continues to

increase such as in West South Central. This indicates that the impact of an increase in energy prices on disembodied change outweighs in all regions the impact of reduced rate of learning and embodiment. Overall, total energy intensity declines as a result of an increase in the cost of carbon, indicating that the increase in disembodied technological change slightly outweighs the decline in embodied technological change. This decline translates to substantial savings in energy expenditures, ranging from xxxx in West South Central to xxxx in Mid Atlantic in 2010, when compared to the base scenario.

- On average WURs decline which by definition indicates increase in the share of virgin fibers and also an increase in expansion potential of the share of self-generated energy in total energy use. This occurs because firms, which use recycled fibers as their main fiber source and firms that use mechanical pulping, must purchase most of their energy and are not able to sell (on net) energy into the grid. As a result, as energy prices increase, processes that use waste-fiber pulping and mechanical pulping are harder hit than firms that pulp virgin fibers using chemical pulping processes. Those firms are able to meet most of their energy needs through self-generation and may be able to feed some of it into the grid. Even if waste-fiber pulping in *total* is less energy intensive than the chemical pulping of virgin fibers, it is more energy intensive when only purchased energy needs are accounted for.
- Net carbon intensity declines in all regions at a considerably faster rate than total energy intensity. The decline beyond the decline in total energy intensity is the result of a policy facilitated shift towards less carbon intensive fossil fuels and towards increased self-generation of carbon neutral energy (see Figures 5 and 6).
- Gross carbon intensity however, increases beyond what it was in the base scenario as a result of significantly reduced recycling rates, and thus increased waste-paper accumulation in landfills in addition to the continued shift to self-generated energy (figure 7).

INSERT FIGURE 5 HERE

INSERT FIGURE 6 HERE

INSERT FIGURE 7 HERE

Co-benefits and costs of policy

- An increase in the cost of carbon has the intended effect to reduce net carbon intensity as a result of an increase in disembodied technological change, and moreover, due to the continued shift to self-generated energy. A shift to self-generated energy not only reduces net carbon intensity but also increases energy independence.
- However, an increase in the cost of carbon reduces the rate of embodied technological change, which indicates that the rate of embodied technological improvements declines. The increase in disembodied changes only marginally outweighs the decline in embodied change. Thus, a 100$ increase in the cost of carbon only has marginal impact on energy intensity and is not able to overcome the significant capital inertia in the industry. Also, because disembodied changes are often reversible due to very small capital costs, a decline in intensity due to disembodied changes are less

permanent than if they occurred due to embodiment, and in the case of declining energy prices are likely to be reversed. We might conclude, therefore, that a price driven climate policy is not likely to facilitate permanent change in this industry.
- An increase in the cost of carbon reduces the use of recycled paper and waste-fiber utilization rates, and increases gross carbon intensity. This increases virgin fiber intensity in the industry, and because the virgin fibers provide lower yield than waste-fibers, fiber intensity increases.
- Substantial regional differences are observed and clear winners and losers emerge. Regions heavily reliant on waste fibers are clearly disadvantaged, and production shifts to Southern regions that more easily are able to fulfill their energy needs through energy self-generation.

Discussion

This paper describes a dynamic computer model that captures physical energy and material flows as a function of engineering and economic factors, using a capital vintage framework. Model results illustrate the potential conflicts in trying to simultaneously increase energy efficiency in the industry, increase the share of self-generated energy and increase the share of wastepaper as well as reduce carbon emissions. This result underscores the observation that a change in one input has important implications for other factors of production and trade-offs in waste flows.

The results further illustrate the danger of unduly narrowing policy options to affect energy prices while ignoring the impact on material flows and waste-management. An increase in energy prices could reduce WURs and therefore increase gross carbon intensity since methane intensity would increase. This result depends on the assumption that the share of non-recovered paper that is landfilled remains constant, and that the capture of methane gas from landfills does not increase.

The long-lifetime of capital in the sector, low rates of capital turnover and capital intensity, in addition to the significant impact of embodied technological change, indicate that an increase in capital turnover is the most important factor in permanently changing carbon and energy intensity profiles in this industry. The immense capital intensity and capital inertia ensures the capital stock changes very slowly and thereby will only gradually improve energy, carbon and fiber efficiencies as we observe. As a result, investment incentives to prompt the industry towards a more efficient technology trajectory and thus enable the industry to take advantage of considerable cost–effective energy efficiency improvement potentials that currently are available in the United States (Martin et al. 2000), in addition to prevent simultaneously a decline in the use of recycled fibers, may be the way to go. Such incentives and programs may have little visible impact initially but their impact will become more pronounced as their effects ripple through to alter the structure of the capital stock. Without incentives to replace existing capital, technological change will remain incremental and material and energy use and carbon emissions from the pulp and paper industry will continue to increase into the foreseeable future. As a consequence, policy-makers should put into place early and consistent incentives that assist in the retirement of old inefficient capital stocks, ensure that policies do not discourage capital retirement, and pursue policies that shape long-term patterns of capital investment. Grand-fathering rules are in conflict with these insights (Gray and Shadbegian 2001). Programs consistent with the insights generated by our analysis include investment tax rebates, demonstration projects to reduce investment uncertainty in new technology reducing hurdle rates in the industry and voluntary sector agreements (Worrell et al. 2001). However, such policies are likely to go unnoticed if the modeling tools used for policy analysis do not enable integrated analysis of input and waste flows in addition to ignoring capital structure and investment behavior in industry.

The results indicate that an increase in energy prices will not facilitate a permanent change and cannot overcome capital vintage effects – but will rather facilitate fuel switching and disembodied changes in efficiency and in addition have serious regional implications. Consequently, to enhance the long-term sustainability of this particular industrial system, policies need to provide investment incentives to facilitate faster turnover of old capital, which would result in permanent changes in material and energy flows.

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Census Region	**Average Energy Intensity (million BTU's/ton output)**	**Self-generated Energy - % Share**	**Wastepaper Utilization Rates (%)**
New England	21.54	47.9	0.36
Mid Atlantic	18.80	29.3	0.54
East North Central	20.34	37.5	0.50
East South Central	34.16	61.5	0.22
Mountain and Pacific	24.82	42.6	0.42
South Atlantic	42.89	63.0	0.29
West South Central	34.16	61.5	0.22
West North Central	20.34	37.5	0.50

Table 1. Regional average energy intensity, fractional share of self-generated energy and waste paper utilization rates in 1998. Source: AF&PA various years.

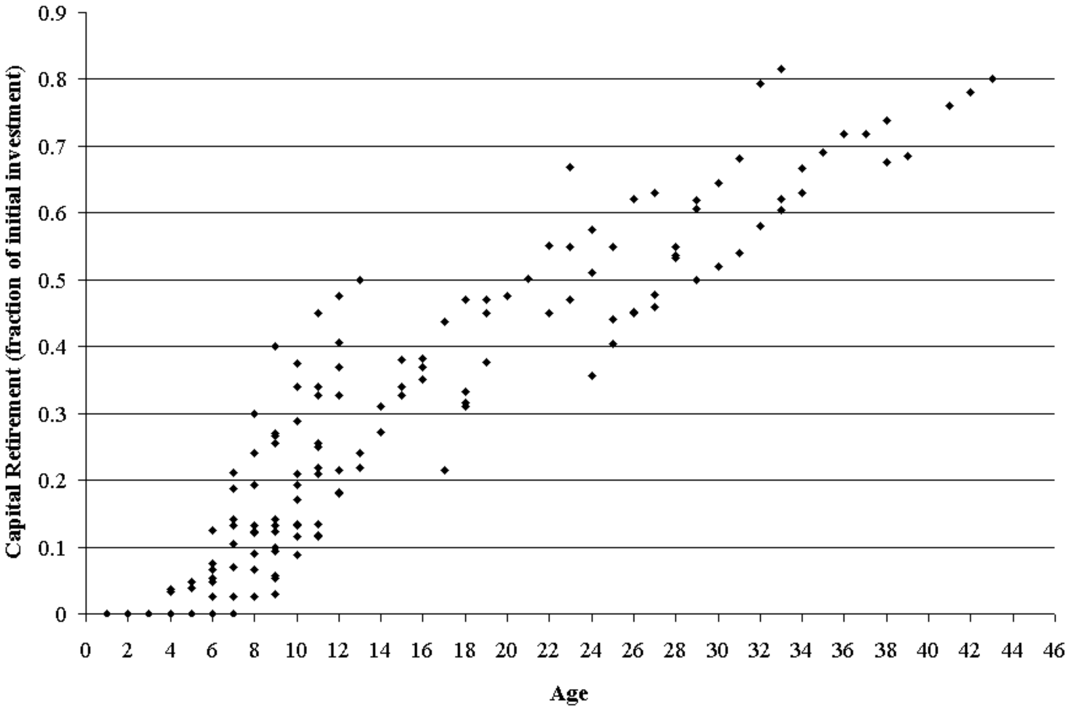

Figure 1. Cumulate replacement rates by vintage (calculated from AF&PA, various years).

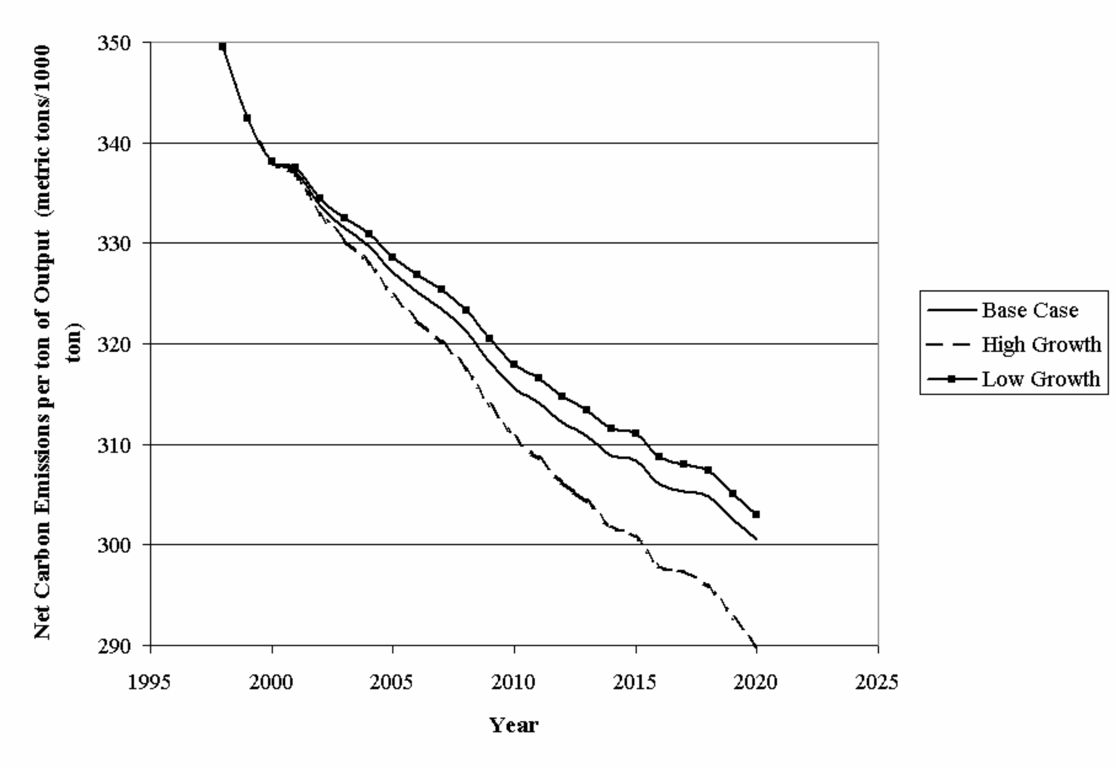

Figure 2. Net carbon intensity in East North Central

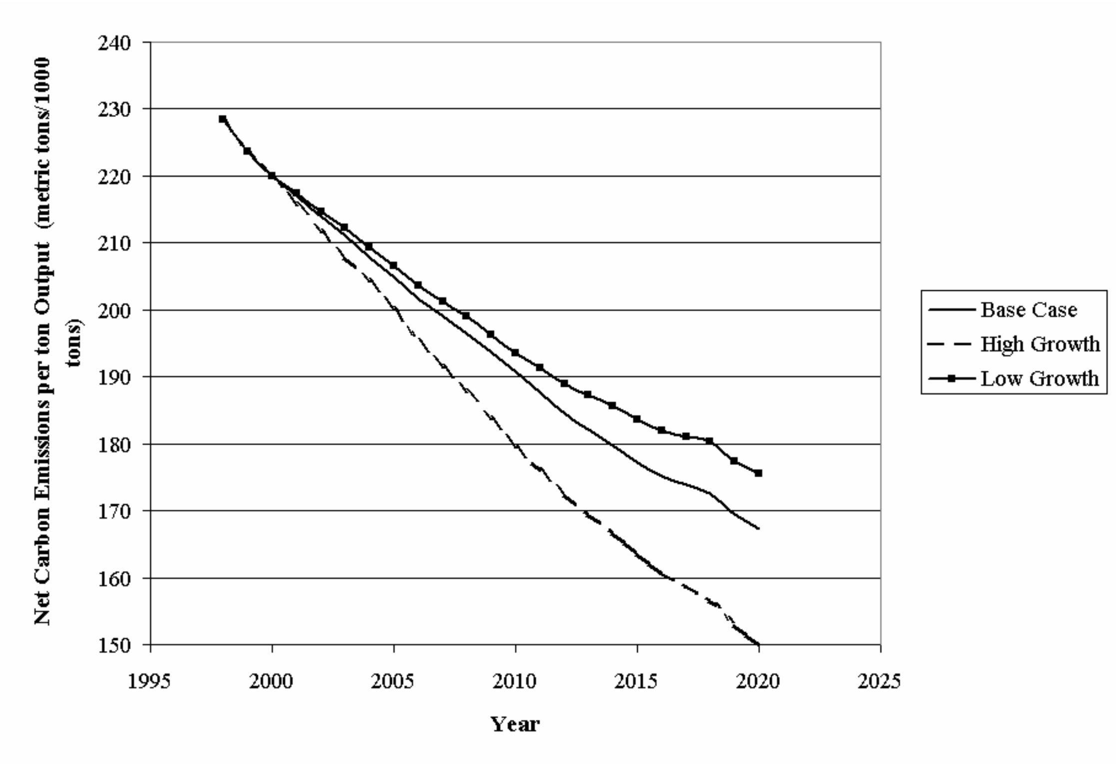

Figure 3. Net carbon intensity in East South Central

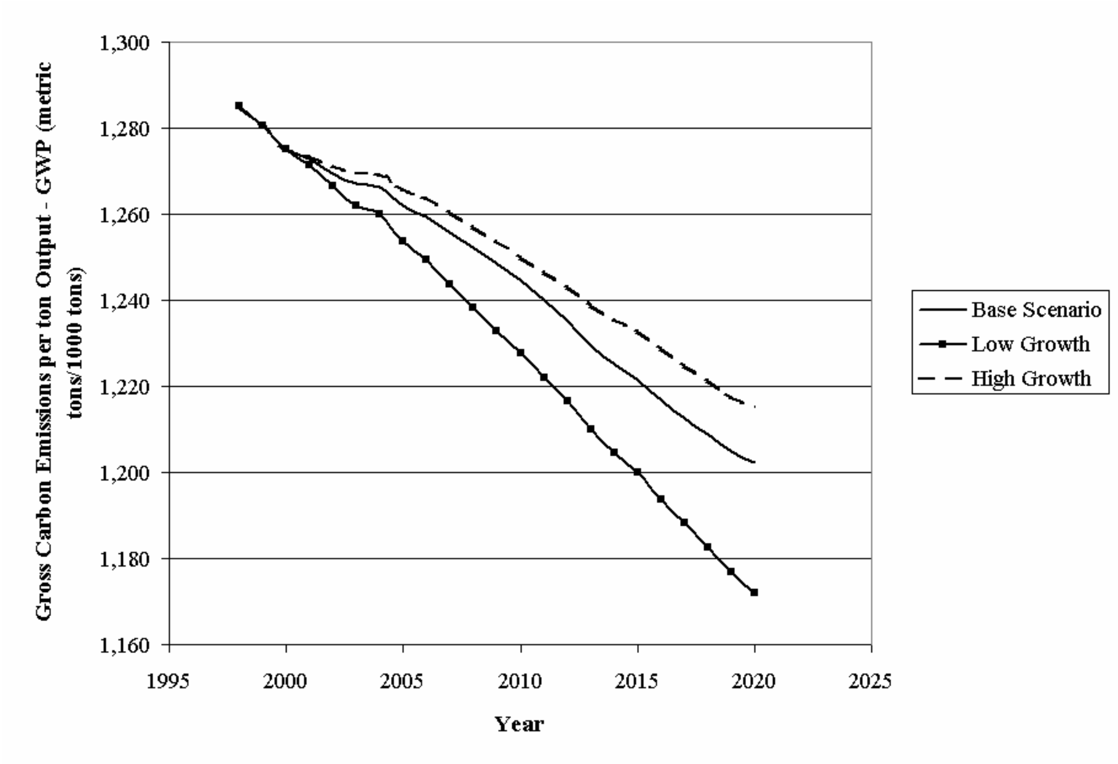

Figure 4. Gross Carbon intensity (GWP). Base case, high and low growth case.

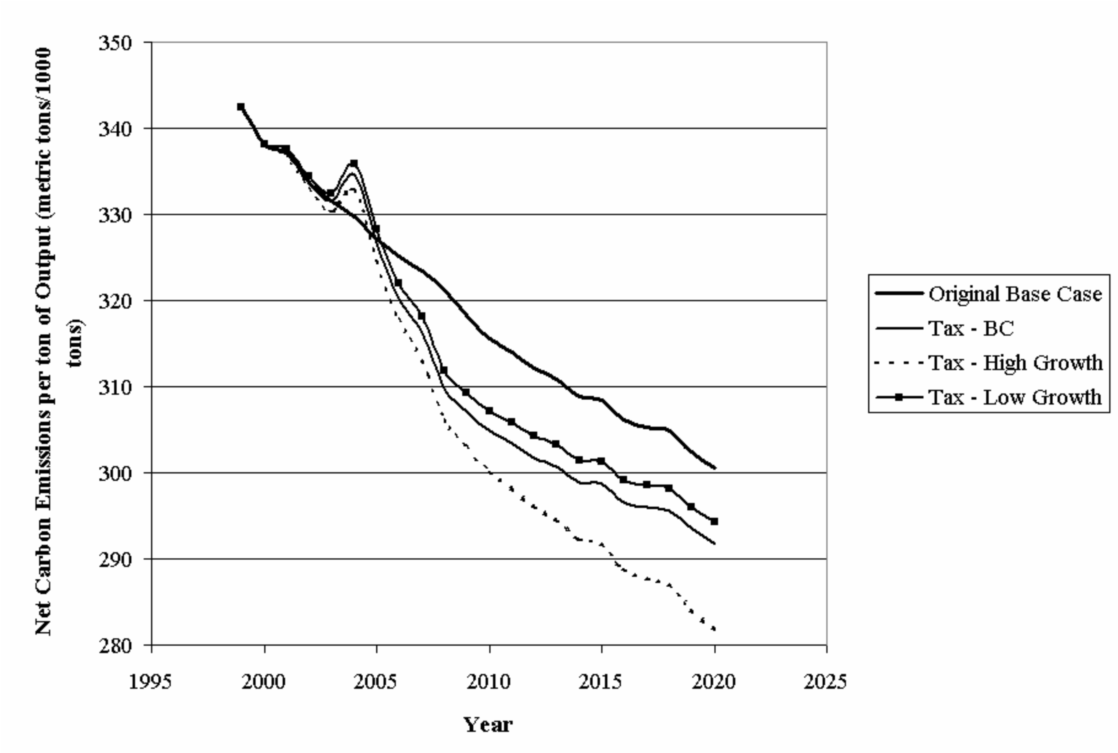

Figure 5. Net carbon intensity in East North Central when the cost of carbon increases by 100$.

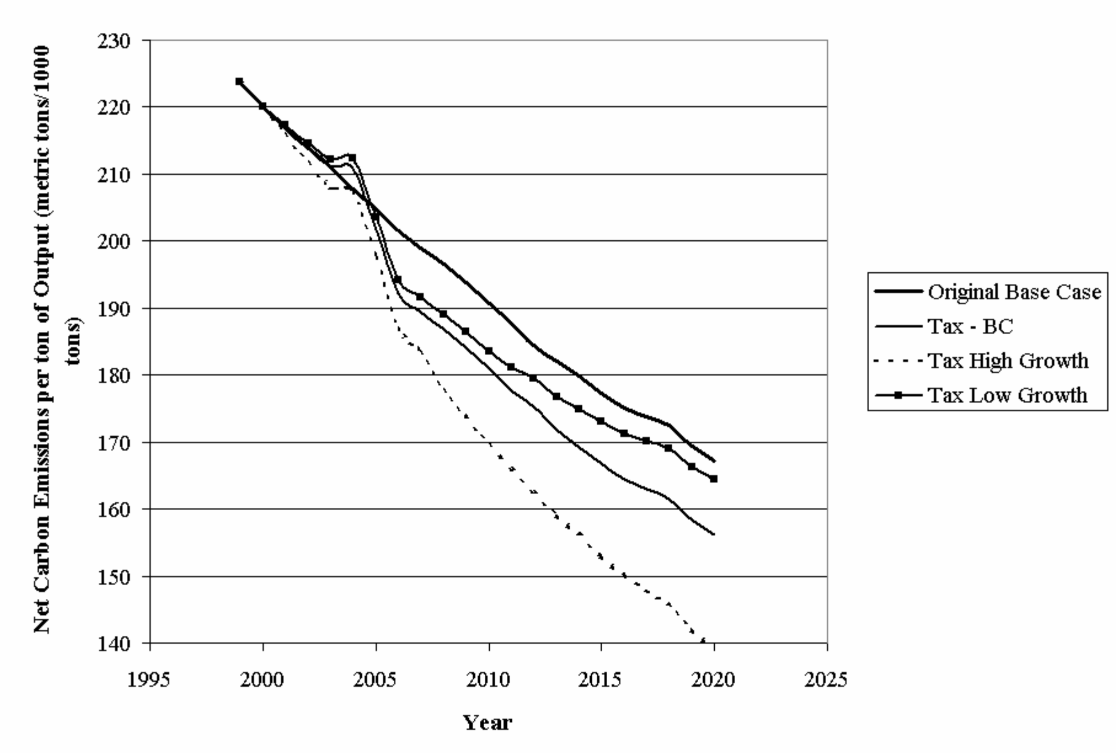

Figure 6. Net carbon intensity in East South Central when the cost of carbon increases by 100$.

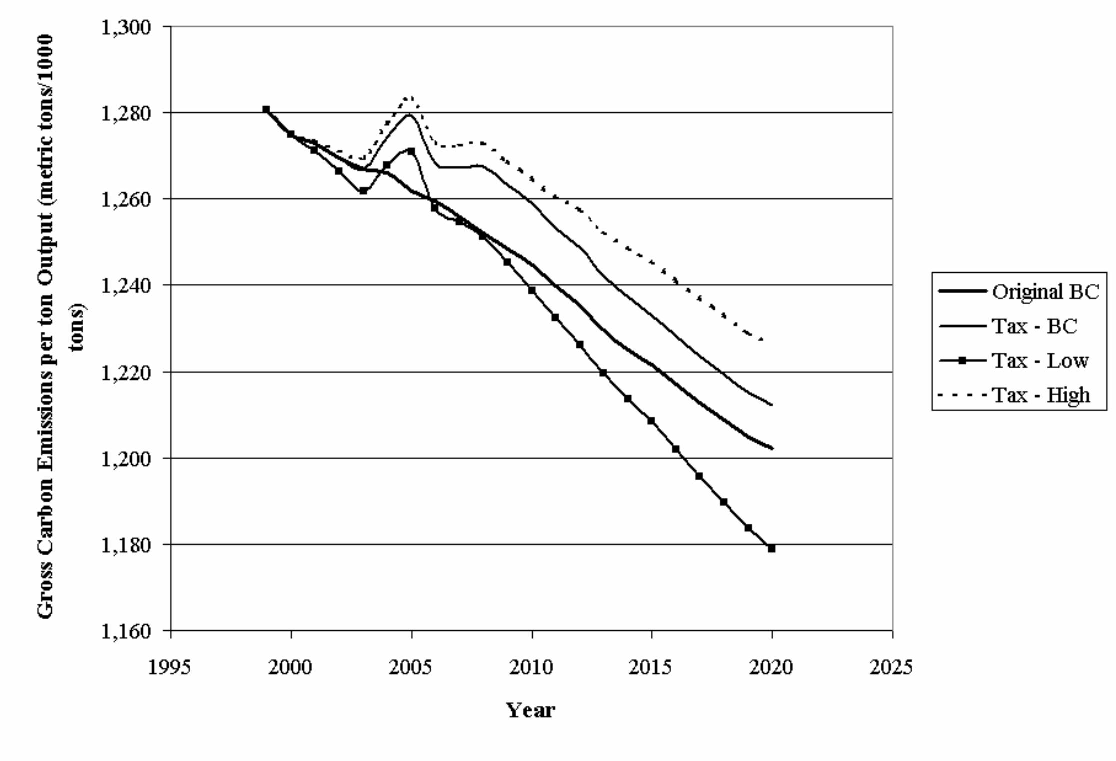

Figure 7. Gross Carbon intensity (GWP). Base case, high and low growth case

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