Modeling Industrial Behavior and Feedback Between Energy and Material Flows and Capital Vintage: Implications for Material, Energy and Climate Change Policy Design

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ABSTRACT

The goal of this study is to present a framework for quantifying the relationship between physical energy and material flows, capital structure and investment behavior in the US paper industry to the end of analyzing potential conflicts between energy and material use policy and goals for greenhouse gas emissions. A regional econometric - engineering vintage model is developed which simultaneously incorporates investment decisions, physical material and energy flows, as well as incorporates directly the vintage structure of the capital stock – capturing the impact of capital inertia which in a mature industry greatly influences technological change and thus investment/management decisions. Each vintage or age-class of installed capital is specified by age-specific retirement rates, fiber, and energy intensities. Both embodied and disembodied technological change, are incorporated, as well as carbon dioxide emissions from fuel use and landfill methane generation.

Results demonstrate the interdependence between material and energy flows and the central role energy prices have in decision-making. For instance, in the quest to reduce carbon emissions through fuel switching and improvements in energy efficiency, policy-makers may want to increase the price of fossil fuels, based on their carbon content. Yet, this policy will disadvantage the use of waste-fibers, and thus discourage paper recycling which of course has important implications for greenhouse gas emissions as well as for the ultimate impact on energy efficiency. The results highlight the importance of taking a systems perspective, incorporating simultaneously material and energy flows, when estimating the impact of policy on increased sustainability of industrial systems.

Introduction

The analysis of industrial systems rests on the pillars of the first and the second law of thermodynamics, which e.g. infer that each industrial system cannot create nor destroy matter. Industrial processes thus only rearrange materials into desired form necessitating at least a minimum amount of materials and energy for each production process. In addition, whatever enters an industrial system in the form of matter will exit the system, broken into useful output and waste (Ayres 1978). As a result, industrial processes can be thought of as physical transformation processes, quantified by the magnitude and structure of physical material and energy flows, quantifying the absolute link between inputs, useful output and waste (Graedel & Allenby 1995). Yet, physical flows do not exist in isolation from economic variables since any change in physical flows, be it to improve energy or material efficiency, or to change the material or energy mix used in a production process, is influenced by economic decision-making. Expanding the boundaries of conventional physical flow analysis to include both energy and material flows and the economics of change facilitates a descriptive analysis into alternative energy and material futures as a function of economic drivers.

Such expansion will enable the analysis of an industry as a dynamic integrated system, effectively linking the physics and economics of material and energy flows, and thus simultaneously accounting e.g. for the anticipated (positive or negative) impact of policy on a multitude of media. For instance, paper production is based on material and energy flows which both influence the carbon cycle. The main material inputs into papermaking are either waste or virgin fibers. The energy inputs consist of fossil fuels and selfgenerated energy. The industry has the choice either to use waste-fibers as a fiber or energy source or to discard them into landfills generating methane. Since on average the pulping of waste-fibers uses more purchased fossil fuels per ton of pulp than chemical pulping techniques (Energetics 1990), a policy that aims at reducing carbon dioxide emissions may reduce the incentive to use recycled fibers, and thus potentially increase the rate of future methane generation in landfills. An integrated systems analysis of the economics of physical material and energy flows can reflect upon such potential relationships and on the impact and response to policy. This paper describes the development of a capital vintage framework which enables the quantification of the relationship between physical energy and material flows, capital structure and investment behavior in an industrial system to the end of analyzing potential conflicts between energy and material use policy and goals for greenhouse gas emissions. The industrial system chosen for this study is the US pulp paper industry (SIC code 26 or NAICS code 322).

The Drivers of Industrial Change

The capital stock of each industrial system is built of numerous age classes (vintages) of which each has its own characteristics. Such 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.

An industrial system "evolves" as the capital stock changes, through an expansion of the capital stock or through the gradual replacement of old worn out or depreciated structures. The expansion of a capital stock will, by definition, increase the use of input materials and slightly improve material and energy efficiency – given that the industry invests in more efficient capital. On the other hand replacement investment will more extensively increase energy and material efficiency, as well as keep constant or reduce total use of material and energy inputs. Thus, the "evolution" of a mature industrial system incrementally changes the flows of material and energy into and out of the system and can be characterized as technological change.

Technological change can either be embodied (Solow 1957) or disembodied. Embodied technological change encompasses the three stages of change - invention, innovation and diffusion through which the innovated invention becomes embodied into the capital stock (Schumpeter 1939). Embodied technological change thus requires substantial capital investments both by the industry investing in the new capital (diffusion) and by those participating in the earlier stages (invention and innovation) via e.g. research and development expenditures. Since embodied change only occurs through new investment it only influences the input efficiency of the youngest vintages (Berndt Kolstad & Lee 1991).

Learning influences the speed of diffusion, since learning gradually decreases investment and/or operational cost and as the speed of diffusion increases, the cost of investment declines faster as a function of learning. Despite the positive, seemingly self-feeding feedback relationship between diffusion and learning which leads to increased rates of diffusion, the evolution of an industrial system is not spontaneous and random but a function of substantial investment costs which are forced to a particular direction due to path dependency. Thus, the choice which innovations will diffuse is influenced by the existing vintage structure since due to path dependency industries tend to invest in similar technologies as invested in before (Arthur 1994; Unruh 2000). Thus initial technology choices may gradually rigidify and lock an industrial system into a particular technology trajectory (Davidsdottir 2002). Disembodied technological change influences all "older" vintages and is the result of a change in input efficiency as a function of low or no cost operational changes (such an improved housekeeping) in the already installed capital stock (Berndt Kolstad & Lee 1991). Again, learning has a central role in disembodied efficiency changes.

Input substitution within and between input bundles is often equally feasible for each vintage (putty-putty), only feasible for new vintages (putty-clay) or is not feasible for neither new nor older vintages (clay-clay), again linking not only technological change, but also substitution possibilities to the vintage structure of the capital stock.

Thus, to capture changes in physical material and energy flows as a function of technological change or substitution necessitates accounting for the "evolution" and structure of the capital stock, capturing vintage specific features. One way to do this is through capital vintage analysis/accounting, which incidentally easily facilitates the integration of the economics of change and physical flow analysis (Davidsdottir 2002).

The Model

General System Description – The US Pulp and Paper Industry

The organizational structure of the US pulp and paper industry 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 best represented by a competitive market structure[1] (Davidsdottir 2002). For this study the overall industrial system is broken into the 8 census regions, and production within each region is disaggregated into four paper categories (newsprint, tissue, printing and writing, packaging and industrial paper), and four paperboard categories (kraft, bleached kraft, semichemical and recycled).

The industry is one of the most capital intensive industries in the United States with capacity utilization rates averaging over 90%. Technological change has only been incremental, partially as a result of this immense capital intensity, coupled with low rates of capital turnover (equipment as old as 100 years or more is still in use within the industry) and capital inertia – which indeed is to be expected of a mature industry. In this study the regional size and physical vintage structure of the capital stock is accounted for in annual increments to the year 1950. Region specific rates of expansion and replacement investment

[1] For more detailed information on the paper industry and the model see Davidsdottir (2002) and Smith (1996).

coupled with vintage and process specific input efficiencies drive the “evolution” of the system.

Material inputs primarily consist of waste or virgin fibers with a wastefiber-utilization rate (WUR) averaging 35% - yet regionally varying from 20 – 56%. The model captures the flow of materials by type. 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 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 either incinerated or put into landfills. Total fiber use has increased annually at a similar rate as output, and thus fiber intensity has remained approximately constant for the last 25 years.

Total regional energy use by type is also captured, broken to selfgenerated energy (most commonly as a byproduct to chemical pulping processes) and five different purchased fuels. Fuel intensity and fuel mix is regionally heterogenous, where the percentage share of selfgenerated energy in total fuel use ranges from 70 to 30%.

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

Developing the Model

The dynamic simulation model is based on five interacting modules. The modules are:

- **Production module**, which simulates regional production levels and production growth by output type using a reduced form production function where output is a function of input prices, regional income discounted by distance to a demand region, lagged production levels and subject to the total installed regional productive capacity (Kaltenberg & Buongiorno 1986).
- **Physical vintage module**, which describes the size of each vintage in the capital stock and simulates changes in the size of existing vintages and the addition of new vintages as a function of replacement and expansion investment, respectively.
- **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.
- **Input mix module,** which simulates changes in the input mix, i.e. the switch between process fuels and between virgin and waste fibers.
- **Greenhouse gas emissions module,** which describes emissions of methane using the EMCON methane generation module and carbon dioxide using fixed emissions coefficients and the total use of fossil fuels by type.

Parameter estimates are based on time-series analysis of 26 years of historical data (1970 – 1995), vintage-based capital analysis and engineering/physical information.

The physical vintage module. The production module captures by region (k) annual production levels, based on current economic conditions and total physical productive capacity, whereas the physical vintage module captures the size and changes in the capital stock. The capital stock is broken to annual investments back to the year 1950, and future changes in the capital stock are captured using a physical perpetual inventory where the size of the total productive capital stock is described as a function of regional gross new capital investments, the size of last years capital stock (or the sum of surviving past investments) and a vintage specific physical depreciation rate.

Gross new capital investment is a function of expansion investment and replacement investment, where expansion investment is econometrically estimated as a function of input prices and capacity utilization parameters, effectively linking desired production levels to investment decisions. Replacement investment by definition equals the proportion of gross investment that directly replaces retired and depreciated capital. Physical replacement rates are estimated using a Gumpertz curve, and are a function of age of capital (vintage τ), input prices and the enactment of environmental legislation – see more in depth discussion in Davidsdottir (2002).

Input intensity and technological change. To capture total material and energy use, each vintage as it enters the capital stock is assigned vintage specific input (j) intensity parameters. The input intensity of each vintage depends on the output/process mix, and pre-prescribed process specific relative input intensities (RII) of new to old capital (EIA 2000) which either can be a fixed percentage or a function of e.g. R&D spending. Thus the actual aggregate input intensity of new capital (or each vintage) is a function of region and process specific RII's of new to old capital (RIIS) weighted by the relative importance of each process (i) in each region (equation 1), and the weighted average embodied intensity of the existing capital stock ($WAIE_{t-1}^{jk}$) (equation 2). The use of RII's, as estimated by e.g. the EIA for energy (called relative energy intensity or REI) assumes that firms invest in economically feasible best available technologies. The weighted average embodied intensity of the capital stock is a function of the average intensity of all vintages in the capital stock weighted by the relative size of each vintage (equation 3). This approach allows for the incorporation of path dependency into simulations of future directions of embodied technological change.

$$RII_t^{j\,k} = \sum_{i=1}^{8} \left(RIIS^i * \frac{Q_t^{i,k}}{\sum_{i=1}^{8} Q_t^{i,k}}\right) \tag{1}$$

$$EIE_{\tau,t}^{jk} = RII_t^{jk} * WAIE_{t-1}^{jk} \tag{2}$$

$$WAIE_t^{jk} = \sum_{\tau=1}^{T-1} EIE_\tau^{jk} * \left(\frac{I_{\tau,t}^{k} * \left(\frac{Q_t^k}{K_t^k}\right)}{Q_t^k}\right) \tag{3}$$

Input intensity of "existing" capital is influenced by disembodied technological change. Disembodied change according to definition is assumed not to be capital intensive, but is influenced by learning by doing (measured by cumulative production) and input prices.

Disembodiment is assumed to affect equally each vintage in the existing capital stock. Combining the two measures gives the dynamic vintage specific intensity in each time-period ($IE_{\tau,t}^{jk}$) of the productive capital stock, and total input use by type j and region k (TI_t^{jk}) is measured as a function of the dynamic vintage specific input intensity, total size of the vintage (corrected for depreciation) and capital utilization rates (equation 4).

$$TI_t^{jk} = \sum_{\tau=1}^{T} \left(IE_\tau^{jk} * \left(I_{\tau,t}^k * \left(\frac{Q_t^k}{K_t^k}\right)\right)\right) \qquad (4)$$

Thus, the model simultaneously incorporates investment decisions, physical material and energy flows and intensities, as well as incorporates directly the vintage structure of the capital stock – directly capturing the impact of capital inertia.

Input substitution. After total input use is estimated for capital, materials and energy, the input mix is determined. Within each input bundle, substitution is possible based on relative prices and production processes/output mix.

The substitution between energy types is simulated as the simultaneous change in non-quality adjusted fractional shares of each fuel (coal, natural gas, residual fuel oil, electricity, distillate fuel oil, selfgenerated fuels), as a function of changes in relative and absolute energy prices and output mix[2]. Total fractional share of each fuel is then estimated from the simulated changes in the relative fuel shares, and total fuel use by type is a function of the fractional shares multiplied by total energy use from equation 4.

The choice whether to use waste or virgin fibers is estimated as changes in the fractional share supplied by wastepaper. Region-specific maximum wastepaper utilization rates are derived from process specific maximum wastepaper utilization rates (Ruth & Harrington, 1997) and regional process mix. The path towards that maximum is estimated using the Fisher and Pry technology substitution model, driven by input prices, cumulative wastepaper production and recycling legislation. Total use of wastefibers is then estimated as the multiplication of total fiber needs from equation 4 and the wastepaper utilization rate (corrected of course for shrinkage), with virgin fibers accounting for the remainder of the fiber use. To achieve mass-balance in the industrial system as a whole, wastefibers are assumed to come from US produced paper sources and thus produced and used paper products go back into the production stream with one year time lag, where wastepaper use as a source of fibers cannot exceed last years production of paper. The wastepaper that is not recycled is either landfilled or incinerated.

Greenhouse gas emissions. The practices of the paper industry lead both to direct and indirect emissions of greenhouse gases, mostly in the form of carbon dioxide (CO_2) and methane (CH_4). Carbon emitted as carbon dioxide from the burning of fossil fuels is estimated by multiplying total fuel use by type and fuel specific carbon coefficients – yet assuming that selfgenerated energy is carbon neutral. According to Augenstein (1992), carbon emitted as carbon dioxide from landfills amounts to 2/3 of the amount of carbon

[2] E.g. a shift over to increased use of recycled fibers is expected to reduce the potential for further fractional expansion of selfgenerated energy.

emitted as methane, and carbon emitted as methane is estimated using the EMCON methane generation model (equation 5) converted to carbon units.

$$Q_{CH4,\tau} = k*L^{i}_{\tau}*R_{t-2}*e^{-k*(t-\tau)} \qquad (5)$$

The EMCON model (EMCON 1982) in essence packs the solid waste stream into vintages, where each vintage is characterized by the year by which it was landfilled and its composition. Thus, the methane released each year from a particular vintage in the landfill ($Q_{CH4,\tau}$) is a function of the methane generation capacity of the material being added to the landfill (L^{i}_{τ}), the amount of material of each type that is added to the landfill (R_{t-2} which is a function of how much waste is recycled or incinerated), a refuse decay rate coefficient (k) and time that has passed since the material was landfilled ($t - \tau$). Carbon emitted as methane is then corrected for its global warming potential (GWP) and total direct and indirect carbon emissions are the sum of the carbon emitted from landfills and from the burning of fossil fuels.

Parameter Estimation and Simulation Results

After estimating all the necessary parameters – and doing extensive regression diagnostics, the equations presented above are entered into a dynamic simulation software and run simultaneously to examine overall industrial behavior under alternative assumptions. The parameter estimation illustrated the following highlights.

Parameter Estimation

Estimation of the parameters entering the regional production function highlighted the following:

1. Production levels were rarely a function of capital costs, and only in a few instances waste-fiber price was significant with a price elasticity of 0.09 – 0.15. Energy prices were in more instances significant, and substantial regional differences became apparent.
2. Energy price - output elasticity ranged from being insignificant to 0.73.
3. Recycled paperboard on average had most often significant and relatively high price elasticity, ranging from 0.06 to 0.73.
4. In regions where virgin fibers are the prevalent fiber type – the energy price elasticity of aggregate production of paper and paperboard was most commonly very low or zero, yet price elasticity of recycled paperboard was significant and relatively higher than in regions with higher utilization rate of wastepaper.

Those results indicate that an increase in energy prices in regions where waste-fibers constitute a small percentage, may result in a reduction in the wastepaper utilization rate rather than in a substantial decline in production levels. In regions predominantly dependant on waste-fibers (which incidentally are highly dependant on coal as a process fuel which has important implications if the cost of carbon increases), an increase in energy prices is likely to reduce overall production levels, which may or may not result in a reduction in the waste-fiber utilization rate.

Estimation of capital turnover and investment behavior highlighted the following:

1. An increase in input prices in particular energy prices exerts a negative impact on expansion investment.
2. Capital depreciation, and thus replacement investment is significantly influenced by the age of capital and energy prices. Thus as energy prices increase the depreciation curve shifts, effectively reducing depreciation rates for “young” capital but increasing the depreciation rates for “older” capital. Thus the overall impact of an increase in e.g. energy prices on replacement investment depends on the age structure of the capital stock.

Consequently, an increase in energy prices will reduce expansion investment and increase or decrease replacement investment, depending on the structure of the capital stock. As stated before, *ceteris paribus,* both expansion and replacement investment reduce energy intensity whereas expansion investment increases total energy and material use, but replacement investment reduces total energy and material use. Consequently, the national impact on total energy and fiber use is ambiguous and driven by region specific parameters.

Estimation of input substitution highlighted the following:

1. The fractional share of paper produced by kraft-chemical pulping (corrected by the WUR) has a significant impact on the potential shift to increased share of selfgenerated energy. An increase in the fractional share of kraft pulping driven by or combined with an increase in energy prices, facilitates a faster shift to selfgenerated energy, effectively reducing the share of purchased fossil fuels.
2. An increase in fiber prices, has an insignificant impact on the fuel mix, yet a change in the fiber mix, is significantly influenced by energy prices, where an increase in energy prices, slows down the expansion in wastepaper use. Interestingly, fiber prices hardly ever had a significant impact on changes in the WUR.

Overall, an increase in energy prices is seen to reduce the WUR, stimulating an increase in the share of virgin fibers and increase the share of selfgenerated energy.

Simulation Results

The model is run until the year 2020 creating a base case, a high GSP growth case and a low GSP growth case, using exogenously forecasted data of regional input prices (EIA various years; AF&PA various years) and regional income or GSP (BEA various years). The results indicate the following for energy use, energy intensity, carbon emissions and carbon intensity.

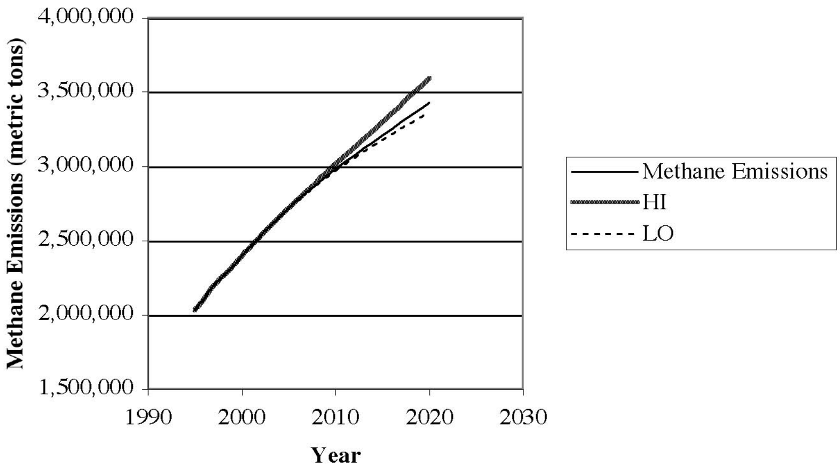
1. Total energy use, use of selfgenerated fuels and purchased fuels are all increasing, as a function of the continued increase in production levels and expansion investment.
2. In contrast, energy intensity is overall declining, but intensity of all fuels (or total carbon intensity) is declining at a slower rate than the decline in energy intensity from

purchased fuels (or net carbon intensity) due to the continued shift towards the use of selfgenerated energy. This in general implies a reduced reliance on purchased energy.

3. Carbon emissions and carbon intensity is significantly influenced by production levels, changes in energy intensity driven by investment behavior, choice of fiber types and shifts in the mix of fuels – which is limited e.g. by the choice of fiber types and output mix.
4. Differences in the regional paths of carbon emissions and carbon intensity are mostly explained by differences in the output mix, WUR's and thus the extension possibilities of selfgenerated energy.

As illustrated in Figure 1 below, methane emissions are on average estimated to increase 2.6% annually between 1995 and 2020 and go from 2 million tons methane in 1995 to over 3 million tons in 2020. This increase is directly related to increased production levels and also due to past paper accumulation in landfills. Output produced today will only gradually contribute to total methane emissions for decades to come. Clearly, higher consumption of paper and paperboard cause methane emissions to increase faster than in the case of lower growth rates since the increase is not outweighed by increased recycling as some regions inch towards their maximum wastepaper utilization rates.

Figure 1. Total Methane Emissions (metric tons)



When estimating total carbon emissions and total carbon intensity (Figures 2 and 3) it becomes apparent that carbon emitted as methane contributes very little to total carbon emissions if not corrected for GWP or approximately 1.8%, but contributes approximately 5% to net carbon emissions (excluding carbon emitted as selfgenerated energy is used). However as presented in Figures 2 and 3, when carbon emitted as methane is corrected by its GWP total carbon emissions increase drastically, as GWP corrected carbon as methane accounts for 31% of total carbon emissions and the reduction in gross carbon intensity slows down in the high growth scenario. GWP corrected carbon emitted as methane, accounts for 53% of net carbon emissions, and thus the impact is even more drastic if we exclude emissions from selfgenerated energy.

Figure 2. Total Carbon Emissions (carbon as methane corrected for GWP)

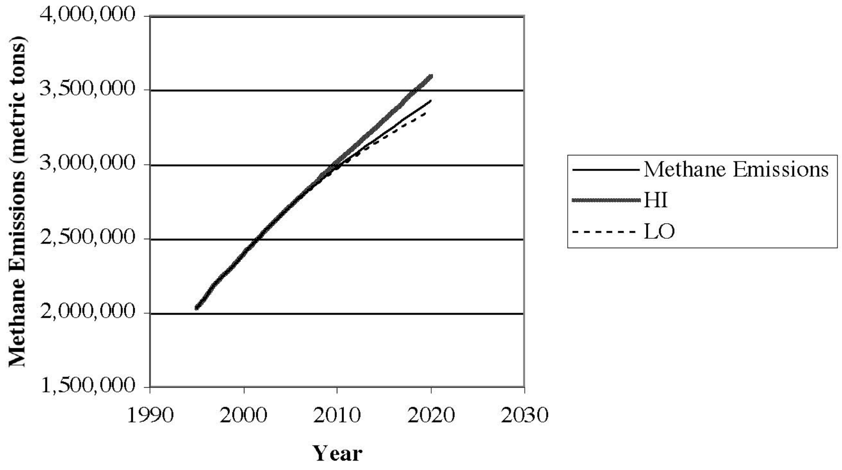
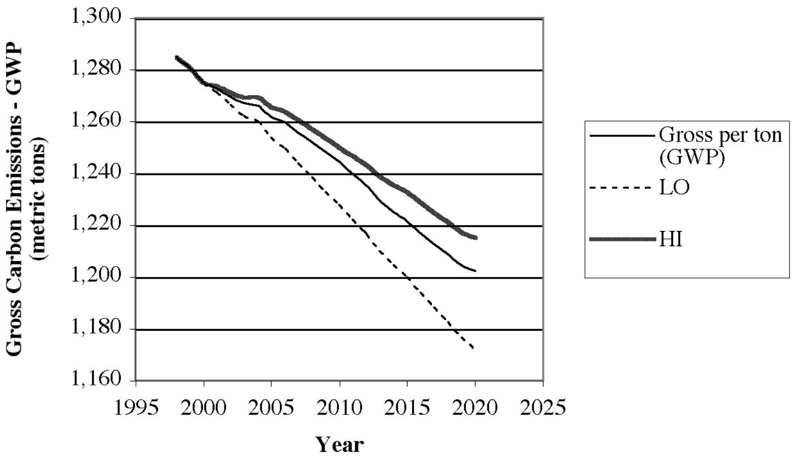


Figure 3. Total Carbon Intensity (carbon emitted as methane corrected for GWP)



Discussion - Implications for Modeling and Policies Aimed at Improving Energy Efficiency

This paper describes the development of a dynamic simulation systems model that simulates the dynamics of physical energy and material flows as a function of engineering and economic factors. The model is regional and contains enough process specific detail to simultaneously be able to reflect the dynamics of an industrial system and to be a meaningful tool to policy and decision-making. The simulations that are generated by the model are not intended to portray the exact paths chosen by the paper industry. I do not pretend to know the future. But, what a simulation can provide is an indication of future production levels, technology choices, physical material and energy flows with a direct link to potential carbon emissions trajectories given certain economic conditions. Thus, the real value of the model is not the numerical accuracy of its simulations, but rather the information embedded into the model reflecting relationships (both physical and economic) between important components of the industrial system as a whole. Those relationships can then be used to simulate in a transparent scenario analysis different futures of the paper industry given various technological and economic conditions.

The value of a transparent scenario analysis is that it can facilitate on the one hand a dialog between modelers and industry representatives, allowing the industry to view and appreciate the different futures that are feasible, given different economic and technological conditions. Thus, the model and its base analysis can be used as a starting point for a conversation on the common goal to analyze the potential for reducing carbon emissions without displacing them elsewhere. Of course, currently there are numerous issues excluded from the model such as the impact of an increase energy prices on income, and the impact of trade on the growth of the paper industry.

Nevertheless, the research presented in this paper highlights the importance of using a dynamic systems approach when examining complex industrial systems, which flushes out important relationships, which would not be found, in separate analyzes of changes in energy and material use and the shares of material and energy types. The model results illustrate the potential conflicts in trying to simultaneously increase energy efficiency, increase the fractional share of selfgenerated energy and increase the share of wastepaper. In terms of improving energy efficiency, we must clearly specify if the goal is to reduce the purchased energy intensity or total energy intensity. A price based energy policy, which increases energy prices clearly increases purchased fossil energy efficiency – partly due to fuel switching from purchased to selfgenerated energy, but simultaneously may reduce the use of the less energy intensive wastepaper pulping. An increase in energy prices will also discourage expansion investment and have an ambiguous impact on replacement investment – which is really what we need to increase to stimulate a true increase in energy efficiency.

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