Climate Change Policies and Capital Vintage Effects:
The Cases of US Pulp and Paper, Iron and Steel, and Ethylene

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Abstract

Changes in material use, energy use and emissions profiles of industry are the result of complex interrelationships among a multitude of technological and economic drivers. To better understand and guide such changes requires that attention is paid to the time-varying consequences that technology and economic influences have on an industry's choice of inputs and its associated (desired and undesired) outputs.

This paper lays out an approach to improving our understanding of the dynamics of large industrial systems. The approach combines engineering and econometric analysis with a detailed representation of an industry's capital stock structure. A transparent dynamic computer modeling approach is chosen to integrate information from these analyses in ways that foster participation of stakeholders from industry and government agencies in all stages of the modeling process – from problem definition and determination of system boundaries to generation of scenarios and interpretation of results.

Three case studies of industrial energy use in the USA are presented – one each for the iron and steel, pulp and paper, and ethylene industry. Dynamic models of these industries are described and then used to investigate alternative carbon emissions and investment-led policies. A comparison of results clearly points towards two key issues: the need for industry specific policy approaches in order to effectively influence industrial energy use, fuel mix and carbon emissions, and the need for longer time horizons than have typically been chosen for the analysis of industrial responses to climate change policies.

Key Words
Climate change policy, technological change, dynamic modeling, iron and steel, pulp and paper, ethylene, carbon emissions.

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1. Introduction

The dynamics of industrial systems are influenced by a number of factors internal and external to firms. Understanding these dynamics as well as the underlying factors and the feedback relationships between them will be key to judging the influences that individual policies have on energy and emissions profiles of industry. If, for example, constraints on technological and managerial improvements are underestimated, then the future energy use and emissions of an industry may exceed expectations. As a consequence, policies implemented today to reduce energy use or emissions may be too lax to achieve desired energy efficiency and environmental performance goals. Conversely, assessments that are primarily guided, for example, by an analysis of periods in which an industry only has changed slowly, then future reductions in material use, energy use and emissions are likely to be underestimated if the constraints, which were relevant in the past, are no longer as binding. Such underestimates may potentially prompt policies today that are overly restrictive and may possibly even hamper future environmental and economic performance of an industry – higher than necessary taxes may be levied or tougher prescriptions for technology choice may be implemented.

For the study presented here, we collaborated with the US Environmental Protection Agency and industry representatives to explore the likely consequences of climate change policies for the US pulp and paper, iron and steel and ethylene industries by building dynamic computer models of industrial behavior. The goals of the project were to build models which helped assess potential energy and carbon emissions profiles of these three industries in response to different policies and to include investment and policy decision makers from industry in the various stages of the assessment process.

In the first section of this paper we present some of the methodological challenges as well as the challenges for decision support, which we encountered in the process of developing the three industry models. The subsequent section of the paper details the three case studies – one each for the US pulp and paper, iron and steel, and ethylene industry – followed by a generalized description of the models and a discussion of model results. The paper closes with a set of lessons for the design of climate change policy.

2. Challenges for Dynamic Industrial Systems Analysis

In this section of the paper we address some of the main issues or challenges that we encountered when developing models of industrial energy use and carbon emissions. This section is divided into a discussion of methodological challenges and challenges for decision support.

2.1. Methodological Challenges

2.1.1 ***Defining System Boundaries***

The first issue any system modeler has to tackle is the specification of system boundaries appropriate for analysis. Industrial systems are complex, hierarchical systems – encompassing a plethora of processes and technologies that are highly interconnected at the firm and industry levels. Adjustments in one process or sector may require, or presume, adjustments in other processes or segments of that industry or other sectors of the economy.

In principle, input-output analysis, and specifically energy input-output analysis (Hannon 1973, Bullard and Herendeen 1975, Bullard et al. 1978) may be used to trace energy use implications that changes in one part of the economy have for the performance of other parts of the economy, and to explicitly account for the indirect effects that such changes may have in the economy as whole. Unfortunately, because of data limitations and methodological challenges input-output analysis is often difficult to apply within a dynamic context at the detail relevant for decision makers in industry.

Since it is often not entirely clear a priori what constitutes a specific industry, it becomes even more important to retain process-specific information for industrial systems analysis. As system boundaries change, new processes may be added or some that were previously considered, removed. Furthermore, how an industry may be defined for analytical purposes can vary significantly depending on the purpose of a study. For the steel industry, both markets of inputs and outputs differ between integrated mills and electric arc furnaces and as a consequence analyses of the markets on which the steel industry operates will differ if both parts of the industry are treated separately or lumped together into one aggregate. Similarly, because the different parts of the steel industry use fundamentally different technologies, an assessment of the impacts of steel production on environmental quality will differ as well. For example, a significant share of energy use and emissions by electric arc furnaces are generated in the electricity sector of the economy. A shift from integrated mills to electric arc furnaces will thus have fundamentally different implications for the industry’s energy use and emissions profiles if off-site electricity generation is accounted for or not.

We have chosen a modeling approach that enables us to capture specific production processes with sufficient detail to be relevant and meaningful to decision makers at the process level and, at the same time, provide opportunities to capture the ramifications of process-specific changes at the industry aggregate. For example, the model of the iron and steel industry disaggregates the industry into major processes of coke production, blast furnaces, basic oxygen furnaces, and electric arc furnaces, and all models contain information on how the electricity they are using has been generated, and what the associated carbon emissions are.

2.1.2 Representation of Industry Dynamics

A further challenge for research dealing with causes and potential future trajectories of industrial energy use and carbon emissions is associated with the treatment of industrial change through time which is driven by capacity expansion and the turnover of the capital stock. Many analyses of industrial systems performance for climate change policy assessment use general equilibrium models. These models typically describe, at a point in time, interactions among demand and supply of marketed inputs and outputs, characteristics of technologies, such as energy efficiencies and emissions coefficients and policy variables, such as subsidies and tax rates given perfect foresight, efficient markets, and perfect mobility or malleability of the various factors of production (e.g. Goulder 1995, Goulder and Schneider 1999). A set of equations is solved for prices that achieve equilibrium at a point in time on the various energy, material, labor and product markets captured in the model. Then a set of new technological or policy conditions are imposed for a subsequent period for which the model is solved. Comparison of model results from period to period can then be used to infer potential industrial change over a series of equilibrium points.

An alternative viewpoint posits that industrial systems are in constant flux, or disequilibrium. Choices of "optimal" investment in new technology are guided by essentially unknown future conditions on input and output markets and thus perfect foresight is not obtainable and instead behavior may be myopic. In addition, since there is often a significant time-lag of several years between investment into new capital and bringing that capital on line in the production process, investment that may be optimal from the perspective of one point in time may be too large or too small by the time that capital can actually be used (Jorgenson 1996). As a consequence of uncertainties and time lags, industry continuously adjusts its investments in efforts to close the gap between desired and actual investment, yet is unlikely to be ever in equilibrium.

To capture the constant adjustment of the capital stock all three models described below we use Jorgenson's perpetual inventory method. The capital stock never perfectly reaches its "optimal" scale and is constantly being adjusted based on current economic conditions.

2.1.3 Representation of Technology

Closely related to the choice of equilibrium or non-equilibrium perspective are the ways in which technology is represented. One convenient representation of production processes is with aggregate production functions that relate quantities of industry output to input quantities. For purposes of convenience and analytical tractability, aggregate production functions are typically assumed to meet certain mathematical criteria, such as substitutability between inputs and homogeneity of the capital stock (Doms 1996). The latter assumption may prove problematic when investments are lumpy, occur at irregular intervals, and when technical change leads to marked differences between existing and new capital.

As an alternative to using aggregate production functions, an industry's capital stock may be disaggregated into different age classes, which each may be characterized by vintage-specific efficiencies, substitution possibilities and capacity utilization rates. Aggregate industry performance is then a function of the industry's capital vintage structure (Mulder et al. 2001).

Since a vintage analysis avoids the assumption of a homogenous capital stock it enables an explicit analysis of the vintage related potential of input substitution via putty-putty, putty-clay and clay-clay models of technological change. In putty-putty models perfect input substitution is equally possible for new and existing capital, in putty-clay models perfect input substitution is only possible for new capital and in clay-clay models substitution between inputs is possible neither for new nor for existing capital (Mulder et al. 2001, Jacoby and Wing 1999).

The choice of an appropriate representation of substitution possibilities depends upon the level of aggregation. In highly aggregate models, such as models that represent the entire manufacturing sector as one aggregate, a putty-putty representation may be appropriate whereas in models examining a particular technology a clay-clay representation may be appropriate since little flexibility is available within individual technologies. A model of a particular industry falls somewhere in between the two levels of resolution, and is likely to be best represented by a putty-semi-clay representation. A putty-semi-clay representation implies that perfect substitution is possible for new capital, but for existing capital only limited substitution is possible.

Technological change defined as a reduction in the intensity of use of one input while holding the intensity of other inputs constant, may occur either in embodied or disembodied form. Embodied technological change occurs as a change in input efficiencies of the capital stock and can be brought about through investment in new, more efficient technologies (Solow 1957). Thus it is through investment in new capital that these more efficient technologies become embodied into the capital stock. Yet, the structure of the existing capital stock influences the choice of what kind of technologies are being invested in – commonly called technology lock-in or capital inertia (Arthur 1994). Disembodied changes imply low cost changes in the input efficiency of the already installed capital stock, such as through improved housekeeping and learning (Ross 1991a and b).

The two types of technological change influence new and existing capital in different ways. The character of existing capital influences the choice of new technology and the potential for input substitution varies between vintages. A heterogeneous representation of the capital stock is important to reflect actual dynamics of technological change at a level that matches experiences of decision makers in industry and policy, and to adequately portray input substitution associated with technology choice. This is the approach we have chosen for the models described below.

2.1.4 Bottom-up and Top-down Modeling

Perhaps most frequently debated in the energy and climate change modeling literature is whether to choose a bottom up or a top down approach for the representation of energy use technologies (IEA 1998). The bottom-up perspective relies on detailed information about the cost and performance of individual technologies to choose the appropriate combination of energy using technologies to minimize the cost of energy use.

The top-down approach does not represent individual technologies but rather examines the impact of policy on aggregate energy demand and aggregate energy efficiency. The two opposites frequently reach very different conclusions regarding the cost of carbon emission reductions – the bottom-up approach is often considered overly optimistic and the top-down approach too pessimistic. The former often suggests that many reductions in emissions can be reached at low economic cost or even at economic benefits, whereas the latter frequently suggests that reductions in greenhouse gas emissions may come at considerable cost to society.

The main reasons for the two divergent conclusions stem from the representation of technology and the possibilities for technological change. The top-down approach assumes that the economy is operating efficiently at its production frontier. Consequently, there cannot exist any "no regrets" efficiency improvement. In contrast, the bottom-up approach accounts for a wide range of (potentially) available technologies – no matter if they are used or not – and thus allows for the possibility that the economy is not operating efficiently, and that there are technologies that can be used at low or even negative cost. However, the bottom-up approach does not account for any market imperfections, such as lack of information, transaction costs, path dependency or inertia (IEA 1998). Ruth et al. (1999) argue that models, which occupy the space in between the traditional bottom-up and top-down models, may be most appropriate for analysis of industrial dynamics in the context of policy change. Such models do include some technological descriptions of the capital stock and combine such descriptions with a top down representation of the economics that stimulate changes in the capital stock. The models that are presented in this study fall into this intermediate category.

2.2. Challenges for Decision Support

In addition to challenges associated with methodological choice and empirical support for studies on the dynamics of industrial systems and their responses to policy intervention, research attempting to inform investment and policy decision-making must be sensitive to, and address the following issues. First, a host of methodological and empirical choices must be made that may ultimately limit the range of policy and investment decisions that can be captured by the resulting model. For example, a general computable equilibrium analysis that represents production by aggregate production functions will be inadequate to investigate the degree to which accelerated depreciation schedules influence the turnover of existing capital within specific industries. Since data collection, data analysis, model development and model calibration are often costly, a compromise must be made between detail and generality with respect to technology representation and between all-inclusiveness of system boundaries and focus of the analysis. This, as virtually any study, presents such a compromise.

Second, modelers must ask whether models should be predictive or descriptive. There is widespread and growing consensus that models of industrial materials use, energy use and emissions cannot be predictive because the real systems such models represent involve a multitude of psychological, technological, economic, and political factors that can never be known with sufficient certainty to be used to predict the future. In light of limited predictability of industrial material use, energy use and emissions, modelers increasingly use models for descriptive purposes only, where the uncertainty regarding model assumptions is acknowledged and incorporated. One way to do so is to play out model scenarios under alternative assumptions about data, functional relationships and investment and policy decisions. Emphasis remains on the model as a computational tool with which to derive insights into potential future systems trajectories, given certain assumptions. This is the primary use of the models developed for this project.

Third, if it is indeed a purpose of an analysis to inform investment and policy decisions, then it will not be sufficient to simply claim in a study's conclusions that there is "policy relevance". Instead, decision makers in the industry and policy arenas need to be involved as judge and jury (Ruth 2001). Which stakeholders to include, and at what stages of a project to bring them in, is important to the credibility of a study in both the scientific and decision making arenas. Ideally, in a democratic society, those who have a stake in a decision should be invited to participate in the decision making process. If the decision is made, in part, on the basis of a formal analysis or model, then stakeholders should be given opportunity to contribute to the identification of relevant system boundaries and level of system aggregation, choice of data, methodology, generation of scenarios, and interpretation of results. In the process of being involved, they may provide valuable information typically not reported in the scientific literature and they may offer challenges to modelers and models that can help either confirm or modify basic assumptions. Of course modelers must try to ensure that stakeholders do not skew the study towards the interests and opinions of a few, but must try to maximize the benefits from stakeholder involvement without suffering from its pitfalls. Extensive expert and peer review processes have helped reflect a wide range of stakeholder perspectives and minimize influence of individual stakeholders or groups.

3. Three Case Studies

3.1 Industry Characteristics

In this section of our paper we describe three case studies of dynamic industrial systems analyses that have been developed with the expressed goal of informing investment and policy decisions at the industry level. The case studies are based on the choices among the methodology options laid out in the previous section: For each industry, we distinguish the energy used to drive the main processes by which raw materials are converted to semi-finished or finished products. Technology descriptions are more detailed than can be found in many other industry models which are designed to explore climate change policies but less detailed than typical for engineering analyses. The choice of model resolution was made on the basis of data availability and feedback from experts in industry and policy, and is discussed in more detail below.

The models use a non-equilibrium approach to portray time-varying behavior in the choice of technology, capacity and outputs, and to trace associated capital stocks through time with the help of capital vintage accounting. We also explicitly model selfgeneration of energy and end use of by-products, as well as electricity generation outside the industry in order to appropriately account for carbon emissions that result from each process and from a switch among processes. The combination of maintaining some degree of detail about processes in each industry, their linkage to essential components of the energy sector in the rest of the economy, and the possibility to dynamically adjust investment decisions through time enables us to explore a wide range of policies that directly or indirectly affect technology choice, such as policies that directly target industrial efficiencies and emissions, or policies that raise the cost of carbon of purchased fuels.

The remainder of this section lays out basic features of each of the three industries and key characteristics of the models that we developed to capture carbon emissions from these industries. Subsequently, we describe in more detail the methodologies behind the models and their results.

3.1.1 Pulp and Paper

The pulp and paper industry is the second most energy intensive industry in the United States. It accounts for over 12% of total manufacturing energy use and contributes 9% of total US manufacturing carbon emissions (Martin et al. 2000). Over 55% of the energy used within the industry is selfgenerated as a byproduct of chemical recovery, with the remainder divided between natural gas, coal, electricity and residual fuel oil. The expansion of selfgenerated energy is limited by the use of chemical pulping processes of virgin fibers, which indicates that increased use of recycled fibers may slow the rate of increase in energy selfgeneration of heat, steam and electricity from waste-to-energy conversion by the industry. Conversely, an increase in the use of recycled fibers reduces total energy requirements in the industry.

In the past two decades new capital expenditures in the paper industry as a proportion of sales have averaged 9%, which is twice the average of all manufacturing industries, and is only matched by the chemical industry (Slinn 1992). Yet, the expansion in output has only been modest and not significantly higher than in other manufacturing industries. These figures thus highlight the immense capital intensity of the industry. A comparison of replacement and expansion investment demonstrates that expansion investment is consistently larger than replacement investment and has resulted in a constant increase in capacity throughout the years without a concomitant turnover of older vintages (AF&PA(b), various years). Equipment as old as 100 years or more is still in use within the industry (Miller Freeman 1997).

Average material intensity has not changed markedly for the last 30 years, yet over the same timeframe energy intensity has changed from 39.3 million BTU's (British Thermal Units) per ton of output in 1972 to 29.32 million BTU's per ton of output in 1998. This represents an annual decline in energy intensity of 0.7%. Despite those gains in energy efficiency, energy use in the industry has continued to increase due to increases in total paper production, which averaged more than 2.9% annually for the last 30 years but has declined in recent years and was 2.2% in 1999 (AF&PA(a), various years).

System boundaries are drawn to enclose both purchased and selfgenerated energy used to drive all the major processes in the production of paper and paperboard, from the pulping stage to refinement of paper products (Figure 1). We exclude the energies used in the forestry sector, to produce capital and to collect wastepaper. Electricity generation is included as a separate model component since electricity accounts for 6% of total energy use in the industry, and thus any changes in electricity consumption is likely to have implications for carbon emissions from the paper industry. Calculation of carbon emissions includes emissions from the use of all purchased fuels and electricity. Emissions from selfgeneration are excluded because such emissions result from biomass based fuels, which may be considered neutral with respect to atmospheric carbon under the assumption that no net deforestation takes place of trees used for pulp and paper production.

3.1.2. Iron and Steel

The iron and steel industry is the fourth most energy intensive industry in the US and accounts for 9% of manufacturing energy use or 2.3% of all energy use (Office of Industrial Technologies 2002). The industry relies heavily on coal as approximately 60% of energy consumed is directly derived from coal and indirectly a considerable share of the electricity purchased is produced in coal-fired power plants. Energy expenditures represent 15-20% of production costs (AISI 2002) which in 1994 translated into a $6.5 billion energy expenditure, roughly 9% of manufacturing energy expenditures in the US (EIA 1997).

US iron and steel is a $57 billion industry with capital expenditures of $2.7 billion or 7.5% as a proportion of sales (AISI 1999). Today, the industry is the third largest producer of steel in the world, producing 54% in integrated mills and 46% in electric arc furnaces. Pressures from other steel producing nations have led to a consolidation of domestic producers in a series of plant closures and mergers, and have prompted increased protection against foreign imports. No new capacity investments in basic oxygen furnaces occurred in the US since the 1960s and future expansions of electric arc-based production significantly depends on the industry's competitiveness with foreign producers.

Integrated mills predominantly use virgin iron ore to produce high quality products commonly used in automobile manufacturing and appliances. The integrated process, however, is highly energy intensive requiring blast furnace temperatures in excess of 3,000 degrees F in order to melt iron ore and to reduce iron oxides to iron and to produce steel. In contrast, electric arc furnaces use recycled scrap steel, are relatively less energy intensive and use electricity to produce their products. During the last 20 years the industry has drastically reduced capacity and increasingly shifted production to electric arc furnaces, which in turn has increased capacity utilization rates and decreased energy consumption. In fact, since the mid-1970s the industry's energy consumption per ton of steel has been reduced by 45% (AISI 2002). The combined effects of increased energy efficiency and decreased production rates has resulted in significant decreases in energy use.

The iron and steel model distinguishes integrated and electric arc furnace production processes. Changes in their respective output shares are, in part, determined by changes in relative energy costs. Integrated production (Figure 2) includes preparation of coke from coal and associated by-products, such as coke oven gas (COG) used elsewhere in the industry as an energy carrier. Also included are production of pig iron from ore and scrap, generation and uses of blast furnace gas (BFG), as well as conversion of several purchased fuels, most notably electricity, natural gas and coal, and the calcination of limestone in basic oxygen furnaces. Carbon emissions result from energy conversions and limestone calcination, and are calculated for each of the aggregate coke oven–blast furnace–basic oxygen route, including carbon emissions from electricity generated off site. In contrast, all carbon emissions from electric arc furnace production (Figure 3) are from electricity generated outside the industry but included in the models. Energy and emissions from the mining of iron ore, recycling of scrap metal and the conversion of raw steel to finished products remain outside the system boundaries of the model.

3.1.3 Ethylene

The US chemicals industry accounts for 25% of manufacturing energy use, 7% of total energy consumption, and 2.6% of carbon emissions (Office of Industrial Technologies 2001). New capital expenditures in the industry as a proportion of sales are over 9% and research and development expenditures are 5%. One of the largest chemical industry segments is devoted to the production of ethylene, which is a principal building block for the production of plastics and resins. The US is the world's largest ethylene producer and currently accounts for 28% of world ethylene production capacity (Oil & Gas Journal 1998). Since 1980, US ethylene production has grown by nearly 5% annually.

In the production of ethylene, hydrocarbon feedstocks – ethane, propane, butane and naphtha – are heated or "cracked" in a pyrolysis furnace, separated into gaseous products and then cooled and compressed into final products (Figure 4). Most of the energy requirements are to carry out the pyrolysis process. Ethylene yield and process energy requirements, are determined by the type of feedstock used and, to a lesser extent, processing conditions such as pressure, temperature and residence time (Worrell et al. 2000). When ethane is used as the feedstock ethylene yields are highest but additional energy needs to be imported. In contrast, the other feedstocks yield relatively less ethylene, yet are virtually self-sufficient in running the cracking process.

The US ethylene industry is based on ethane (45%), propane/butane (27%) and naphtha (27%), which are byproducts of natural gas and oil production. Because the refining industry is the major supplier of raw materials for ethylene production more than 50% of all ethylene plants are located at refineries (Office of Industrial Technologies 2000). Ethylene is produced by cracking hydrocarbons under intense heat and followed by a rapid cooling of the product. The majority of hydrocarbons in the production of ethylene are not combusted as a fuel but rather used as a feedstock and contained in the product itself.

3.2 Methodology

The three analyses of the pulp and paper, iron and steel and ethylene industries contain a set of common elements. The most distinguishing features is the capital vintage component of the models, where the size of the capital stock is measured as installed production capacity in physical units. This component assumes that the capital stock $K(t)$ of an industry in year t is a function of the remaining stock of the previous year $t-1$ and gross investments $I(t - x)$ that occurred in time period t-x and, after the lag of x years, adds to the useable capital in year t:

$$K(t) = I(t - x) + (1-\mu(t))*K(t-1)$$

The deterioration rate $\mu(t)$ is a physical measure of the extent to which capital becomes unavailable for the industry. The deterioration rate is not a constant but is a function of the capital stock's maximum lifetime – its service life - and gross new capital investment, which is estimated econometrically as a function of production levels and input prices. Gross capital investment is defined as the sum of expansion and replacement investment, where replacement investment directly replaces retired and deteriorated capital (that is retrofits). We assume that deterioration and thus retrofits equal a fixed percentage of gross investment, distributed equally across all vintages. In all three industrial systems, the maximum lifetime of the capital stock is fixed (Table 1), and exogenously defined and derived from data reported by government agencies (e.g. EIA 2000) and industry organizations (e.g. AF&PA(b) various years, Iron and Steelmaker various years, Oil & Gas Journal various years).

Capacity (capital) utilization rates are assumed to be uniform across vintages and equal to the average capital utilization rate of each industry. Average capacity utilization is estimated as the ratio between installed capacity and total production volume and thus varies from year to year and is endogenous to the model.

Energy intensity is defined for each new vintage class as a function of the average intensity of the capital stock and the relative energy intensity (REI) of new versus existing capital as described by EIA (2000). Relative energy intensity is a fixed exogenous parameter, which describes the average economically feasible reduction in energy intensity of new capital as a function of the intensity of old capital. Consequently, technological change is simulated as embodied in new vintages, and gradually reduces the energy intensity of new vintages as a function of the intensity of existing vintages and the fixed REI. For instance, if the REI is 0.85 and the average intensity of the existing capital stock is 1000 Btu's/ton, then the intensity of new capital is 850 Btu's/ton. Since the average intensity of the existing capital stock gradually changes every year, the energy intensity of new vintages change accordingly. Changes in the energy intensity of the existing capital stock is influenced by disembodied change and driven either by autonomous change or by energy prices and learning. Switching between individual fuel types is possible and equally easy for all vintages and thus classified as putty-putty. Since substitution is possible for new vintages between energy and capital given the magnitude of the REI but is only possible to a limited extent for existing vintages, total energy and capital substitution is depicted by a putty – semi-clay representation.

A second key feature common to the three analyses is their use of process-specific engineering information to describe target efficiencies, technological limits and fixed engineering coefficients. For example, specifications of potential future process energy use is based on information about best available technology, which, given energy price scenarios generated by the NEMS model, are economically feasible for the industry (EIA 2000). This is incorporated into the models through the use of REI's as discussed above (Table 1). Fixed engineering coefficients are present, for example, in the form of carbon emissions from limestone calcination in blast furnace production.

A third feature common to the three studies lies in the use of time series analyses (historical period covered is 1970 – 1995) to quantify changes in industrial fuel mix, energy intensity, production and demand levels, gross investment and other key variables. For example, all studies make use of seemingly unrelated regressions (Zellner 1962) to capture simultaneity in fuel choice. Simultaneity in fuel choice occurs if an industry expands use of natural gas as a fuel source, then that expansion impacts the choice of all other fuels. Furthermore, all regression equations are subjected to diagnostic tests for heteroscedasticity and serial correlation (Breusch 1978 and Breusch and Pagan 1979).

The capital vintage, engineering, and time series analyses of each industry are combined in a dynamic simulation model that – for each industry – follows a similar structure (Figure 5). A set of equations describes demand and supply interactions on products markets, where demand and supply of a particular output are econometrically estimated as a function of economic variables (e.g. input prices and income measured as GDP/capita). The demand vector drives supply quantities, which are constrained by available production capacity (Table 2). Changes in the capital stock, as discussed above are driven by gross investment, which is econometrically estimated as a function of input prices and desired production volumes. However, gross investment does not influence production capacity until an econometrically specified time-lag has passed (see Table 1). Total energy use in each industry is driven by changes in output quantities and vintage specific energy use per unit of output[1].

As described above the energy efficiency of new vintages is driven by the average input efficiency in the industry and the REI. Over time energy efficiency of existing capital can change as a function of learning or non-capital intensive improvements, such as improved housekeeping practices. The vector which describes total energy use is disaggregated into different energy types, where the total use of each fuel is a function of econometrically estimated fractional shares of each fuel – driven by relative and absolute fuel prices and output mix – and total energy use. One of the energy sources available to the three industries is in the form of electricity generated elsewhere in the economy. To properly attribute carbon emissions associated with a move towards increased use of electricity, each model contains a representation of the US electricity sector using forecasts of potential changes in the national average fuel mix that is used in electricity production as described by EIA (2000).

Total carbon emissions from each industry are calculated by summing the product of fuel specific carbon emission rates per fuel used, and fuel use by type. Great care is taken to not double-count carbon emissions from the use of the various by-fuels generated by any of the three industries. Carbon emissions from the combustion of biomass-based fuels are traced by the model but not reported as a part of total carbon emissions, because carbon emissions from biomass are typically assumed to be neutral with respect to atmospheric carbon concentrations. Furthermore, no carbon emissions are traced for that portion of fossil fuels that enter ethylene production as a raw material, instead of being combusted for their energy content. However, some of the fossil fuels that get embodied in the product are ultimately released into the environment because a share of the materials produced from ethylene ultimately get incinerated. Consequently, we underestimate total carbon emissions to the extent that carbon captured in products is ultimately released into the environment after end use, for example, when decomposition in landfills or incineration take place.

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[1] For technical details of the individual models and engineering and econometric parameters please refer to Ruth and Amato (2002), Ruth and Davidsdottir (2002) and Ruth, Amato and Davidsdottir (2002).

Intervention into the models' dynamics can occur through a variety of investment and policy decisions, many of which can be chosen interactively by model users. To facilitate interaction with the model, a user interface is made available for each model through which users can chose alternative data and functional specifications. User interfaces contain background information on the respective industry, various model components, and instructions for model use[2]. A small set of possible interventions is discussed here.

3.3 Results

For the results described in this section, each model is run first under the assumption that no new external influences are exerted on the industry, such as external shocks to input or output markets, or policies that otherwise affect an industry's choice of input and output. All observed changes are the consequences of the models' underlying assumptions, which are derived on the basis of past observations and engineering parameters. The resulting scenarios constitute a base case against which we compare different alternatives. These alternatives are for various policy interventions. One of these interventions occurs in the form of a policy that raises the cost of carbon-containing fuels by $75 per ton of carbon for fuels purchased by the industry and used as an energy carrier. A $75 per ton of carbon translates into an increase in the price of coal of $1.92 per million Btu, a $1.61 per million Btu increase in the price of residual fuel oil and a $1.08 per million Btu increase in the cost of natural gas. Those fuels used as input into a production process, such as some feedstocks in ethylene production, are assumed to be exempt from the policy because they do not lead to carbon emissions by the industry. The increase in cost of carbon may be prompted by a carbon tax or the need for industry to purchase carbon emissions permits.

A second policy scenario assumes a 10% decline in the energy intensity of new technology relative to the intensity of the aggregate existing capital stock in the industry. This improvement is over and above the efficiency gap that historically existed between new and existing capital in each industry, thus essentially decreasing relative energy intensity (REI) 10% below its historical value. That does not mean that each year capital becomes 10% more efficient than in the previous year – because the efficiency gap is defined on the basis of the aggregate existing capital stock, which e.g. for the paper industry contains the past 35 years worth of investments in capacity. What it does mean is that new capital becomes 10% more efficient than in the base scenario, essentially widening the gap between the efficiency of new capital compared to the average efficiency of the capital stock due to an improvement in the efficiency of new cost-effective technologies added to the capital stock. However, since no new capacity is assumed to be added to basic oxygen furnaces – an assumption widely held in the industry – all REI improvements in the steel sector are for the electric arc furnace route.

Possibilities to decrease the REI by 10% are quite large. For instance, in the paper industry a substitution of the more efficient new black liquor gasification technology for the traditional Tomlinson recovery boilers as the new technology of choice for energy recovery would succeed in reaching that level (Larson et al. 1998).

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[2] To request a copy of the models and software send email to mruth1@umd.edu.

Since capital investments and retirements continuously change an industry's aggregate efficiency, widening the efficiency gap – for example by stepping up research and development and promoting pilot projects – aggregate efficiencies improve faster than they otherwise would, and as a consequence, carbon emissions may be reduced. We refer to the corresponding policy scenarios as "relative energy intensity" (REI) policy scenarios.

A third set of policy scenarios combines an increase in the cost of carbon with improvements in relative energy intensities. Here, we assume an added cost of $25 per ton carbon in purchased fuels used as energy carriers, and a 5% REI improvement below historical levels.

All policies are assumed to be implemented in the year 2002. Each model is run for an annual time step to calculate the resulting market dynamics, changes in input use, and corresponding carbon emissions in each year and across time. To ease comparisons of the impacts that alternative policies have for each industry and across the various industries, we plot for key industry characteristics the observed percentage changes over the last year before policy implementation, i.e. the year 2001. To at least partially reflect the dynamic element of industrial adjustments, we report the percentage changes for two years – 2010 and 2020. For example, Figure 6 shows, for the years 2010 and 2020 respectively, a 7% and 13% decrease in carbon emissions by the iron and steel industry over the 2001 levels. With the increase of $75 per ton of carbon in purchased fuels, carbon emissions reductions are 12% and 16% respectively in 2010 and 2020 (Figure 7). The $75 cost of carbon policy also leads to a more rapid expansion in the share of electric arc furnaces, a slightly larger reduction in energy intensities (measured in Btu per ton of raw steel), a significant lowering of carbon intensities (measured in tons of carbon per ton of raw steel) and reduction in total energy use.

Comparison of the three policies investigated here (Figures 7 – 9) shows that a 10% REI improvement results in less aggressive expansion of electric arc furnace output. To illustrate, in 2010 under the 10% REI policy the electric arc furnace share of output increases by just over 3% while the $75 cost of carbon policy induces a 9% increase. As expected, the mixed policy of a $25 increase in the cost of carbon and a 5% REI improvement leads to changes in electric arc furnace expansion that lies in between the results from the two "pure" policies. However, changes in energy intensity, carbon intensity, energy use and carbon emissions are only marginally different from the "pure" policy scenarios.

A $75 increase in the cost of carbon stimulates expanded use of selfgeneration in the pulp and paper industry (Figure 11) by more than is observed in the absence of new policies (Figures 10) or any other policy (Figures 12 and 13), because of still available potentials in the industry to convert biomass to heat, steam and electricity, and thus cut cost of purchased energy and the increased use of chemical processing as fuel prices increase. However, all scenarios show that expansion of selfgeneration is more rapid for the years 2002 – 2010 than from 2010 onward, indicating decreasing returns to fuel switching and technology change.

Under all scenarios (Figures 10 – 13) only small changes in net carbon emissions by the pulp and paper industry occur because the effect that fuel switching and technology change have on emissions is significantly counteracted by the industry's output expansion. A cost of carbon increase lowers net carbon emissions because of a more rapid switch to (carbon-neutral) selfgeneration. In contrast, policies that stimulate REI improvements provide less of an incentive for that switch to occur, and consequently result in a slight increase in net carbon emissions while industry output continues to rise. Net carbon intensity and energy intensity decline more than in the base scenario – and the most in the $75 per cost of carbon scenario.

Some of the largest percentage changes can be observed for the ethylene industry. Even in the absence of new policies, purchased energy consumption and carbon emissions from purchased energy increase, respectively, by 65% and 194% in 2010 and 41% and 118% in 2020, compared to the year 2001 (Figure 14). Raising the cost of carbon of purchased fuels used as energy carriers by $75 stimulates leads to a lower increase of purchased energy than in the base case (Figure 15). This increase is accompanied by diverting intermediate products within the industry, leaving many of the other key characteristics of the industry relatively unaffected.

A 10% REI policy is by far the most effective approach to cutting consumption of, and emissions of carbon from, purchased energy (Figure 16). The 10% REI policy has more uniform impacts on key industry characteristics than a pure cost of carbon policy. Combining a 5% REI with a $25 cost of carbon increase (Figure 17) leads to results that reflect more the 10% REI policy than the $75 cost of carbon policy, providing strong indication for the overwhelming influence that the existing capital stock has on energy use and emissions profiles. It is worth mentioning that any combination of different REI levels and an increase in the cost of carbon could have been implemented. Different combinations would change the absolute numerical results, but neither the relative differences nor the interpretation of the results. However, the results presented here are roughly comparable to results of several other major studies which use quite different methodologies and data sets (e.g. Interlaboratory Working Group 1998)

3.4 Discussion

Comparisons across industries reveal that cost of carbon and capital-oriented policies, have vastly different implications for energy use and carbon emissions profiles of the three respective industries. These differences are largely attributable to each industry's production and capital vintage structure. For example, the steel industry consists in essence of two different production sectors using very different energy sources and different investment dynamics. An increase in the cost of carbon makes the blast furnace route of steel production significantly more costly because of its high reliance on carbon-rich coal. As electric arc furnaces take over more market share, efficiencies of the aggregate capital stock in that segment of the industry increases because of investments in new, more efficient equipment and learning by doing. At the same time, efficiencies of aging blast furnaces declines because of deterioration, lower capacity utilization, and no positive net investment in new capacity. In contrast, policies targeting relative energy efficiencies lead to less of an increase in the share of electric arc furnaces, and consequently a lower reduction in carbon emissions.

The pulp and paper industry's tendency to selfgenerate heat, steam and electricity from biomass and waste products increases with higher costs of carbon for purchased fuels. As a result of expanded selfgeneration, net carbon emissions (total emissions minus emissions from selfgenerated energy) increase less than they otherwise would.

However, in contrast to the iron and steel industry, improvements in the relative energy intensity of new to existing capital *do* have noticeable positive effects on the industry's total energy and carbon emissions, since a simple increase in REI does not facilitate any fuel switching and thus technological change is unable to outweigh the increase in production level. Energy and net carbon intensities, on the other hand, decline.

Our choice of system boundaries, and in particular the assumption that biomass based fuels are carbon neutral, obviously does influence those results. If carbon emissions from selfgenerated energy would be included, an increase in the cost of carbon would in fact increase carbon intensity due to an increase in the use of selfgenerated energy, which has higher carbon content than other fuels.

These findings are markedly different for the ethylene industry, where process energy is a small share of total energy use, and where, as a consequence, a rise in the cost of process energy would not lead to a noticeable decrease in the industry's carbon emissions. In contrast, studies, which increase the cost of carbon for feedstock energy as well as process energy, find large emission reductions as biomass-based feedstocks replace fossil fuel-based feedstocks (Groenendaal and Gielen 1999). Improvement in the REI of new to existing capital would help replace old capital with more efficient equipment, thus lowering carbon emissions.

A reduction in the carbon and energy intensity of all three industries is dependent upon increased investment in new capital. An increase in capital investment may indeed increase energy use elsewhere in the economy since energy is required to produce capital. Thus, because we do not include the energy required to produce new capital, or the energy required to produce/extract or transport the raw material input we are unable to draw any conclusions on the economy-wide impact of the policies we chose for this study.

4. Lessons for Climate Change Policy

The results of our analysis of energy use and carbon emissions profiles of three capital intensive industries in the US under alternative policy scenarios points at a set of broader issues relevant for the debate of such policies. One such issue raised by the results above – albeit implicitly – lies in the role that modeling can play in exploring implications of alternative policies for future energy use and carbon emissions profiles. Unlike in past (and many present) modeling efforts, emphasis is increasingly placed on models as exploratory tools rather than forecasting devices. By playing out the implications of alternative assumptions about market dynamics, technology change, and policy interventions, modelers hope to identify strategies that are robust under a wide range of assumptions, or that help compare different policies with each other. In their use as tools to facilitate communication among stakeholders from industry and policy circles, models can also become effective focal points that help concentrate on assumptions and issues, and thus sharpen the debate.

The models and results discussed above help identify qualitative differences in the impacts of different policies and indicate that each policy instrument may trigger different kinds of responses by different industries – from shifting production among segments in the industry, as is the case in iron and steel, to changing the fuel mix, as done by pulp and paper, or changing the use of intermediate products, as happening in the ethylene sector. Conversely, various instruments may have different abilities to leverage opportunities in industry to achieve desired policy goals, such as shifts towards renewable energy sources, reductions in total energy use, or reductions in carbon emissions. A mix of policy instruments may be useful to simultaneously improve different industry features.

Second, climate change policy may be designed in various ways. Policy makers may determine an economy-wide or industry-wide emissions target and set in place mechanisms that lead to a change in the price of carbon in order to meet the target within a set time frame – irrespective of the different industries' propensities to respond to changes in the cost of carbon. Changes in the cost of carbon may be prompted, for example, by levying carbon taxes, by removing subsidies for the extraction, distribution or use of fossil fuels, or by requiring purchase of carbon emissions permits.

Alternatively, fixed emissions targets may be set for each industry, while leaving it to industry to figure out how to meet these targets. However, setting such targets individually for each industry requires knowledge of attainable goals for each industry and will require sophisticated accounting methods to ensure that reductions actually take place and are not simply the effect of "system boundary effects" – as could be the case with an industry that in response to emissions constraints purchases more of its inputs from elsewhere in the economy. Similarly, industry-specific targets may limit opportunities for cost-effective emissions reductions by combining forces across sectors – for example, increases in emissions by a supplier may allow for production changes downstream that lead to overall reductions in emissions.

Yet another alternative lies in policy instruments (or policy mixes) – as implied by our analysis above – which have industry-specific features in mind. One instrument (e.g. a carbon tax) may stimulate replacement of carbon-rich fuels while another (e.g. an accelerated depreciation schedule) may speed up turnover of the existing capital stock. While such an approach may be more effective in leveraging the different potentials of different industries to meet environmental goals, it requires considerable information on each industry and may be perceived as unfair if the policies create different (uncertain) economic incidence for the various industries. Collaborations between industry and policy makers may provide unique opportunities and challenges in designing such policies. On the one hand, collaborations do meet the democratic principle of including in the decision making process those parties who are potentially affected by a decision. Collaborations may also reveal information that may otherwise not be available, and build mutual understanding and trust. On the other hand, there is the challenge of policy capture by specific interest groups that needs to be addressed in the policy-making process.

A third issue raised by the results above – and an analysis of capital-intensive industries in general – lies in the relationship between the choice of policy instruments and the time frames over which policies should be evaluated. Past debates about climate change policies have paid notoriously little attention to the capital vintage structures of different industries, often assuming (near-perfect) malleability of capital. In contrast, the analyses presented here point towards considerable capital stock inertia in those three industries. Existing capital stock inertia can lead to large costs of changing energy use and emissions profiles (Lecocq et al. 1998), and extend the timeframe over which the impact of policies is actually seen in the energy and carbon intensity profiles. Capital stock inertia – a common characteristic of energy intensive industries – make energy and emission trajectories rigid, make it unlikely or highly expensive to meet ambitious short-term policy objectives (Jacques et al. 2001) and point to the need for far-sighted policy making. Simply raising the cost of carbon of purchased fuels may be insufficient in overcoming existing capital vintage effects. Alternatively, stimulating research and development in hopes of maintaining a sizeable efficiency gap between new capital equipment and the capital in use in an industry may only make sense if adequate incentives are present to actually replace existing with new capital. Without adequate incentives to replace existing capital, rapid improvements in technology may provide an incentive for decision makers to wait with their investments in fear of locking in equipment that is soon outdated.

Since faster capital turnover requires energy expenditures and carbon emissions elsewhere in the economy, it is not a priory obvious what the net effects of an investment-led policy are. But since both the change in an industry's capital stock and the associated changes in upstream capital suppliers are likely to play themselves out over the course of many years, even more credence must be given to policies that stimulate an increase in the turnover of the capital stock, and thus change carbon and energy use profiles over a longer timeframe. Policies which have the potential to do this are e.g. tax credits for investing in new more efficient technology, R&D subsidies and demonstration projects which reduce the risk/uncertainty of the benefit of new technologies (EERE 2000)

Paying more attention to longer time frames, however, does not mean that short-term goals for emissions reductions can or should be abandoned. On the contrary, meeting long-term emissions reductions goals requires that changes in the existing capital stock are undertaken *now* so that aggregate industry efficiencies improve and so that a basis for learning by using new capital equipment can be generated. Policy must therefore identify how to make short-term and long-term emissions goals consistent with each other, and how to design and implement instruments that leverage industries' unique potentials to meet these short and long-term goals.

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Figure 1. System Boundaries for Pulp and Paper Production.

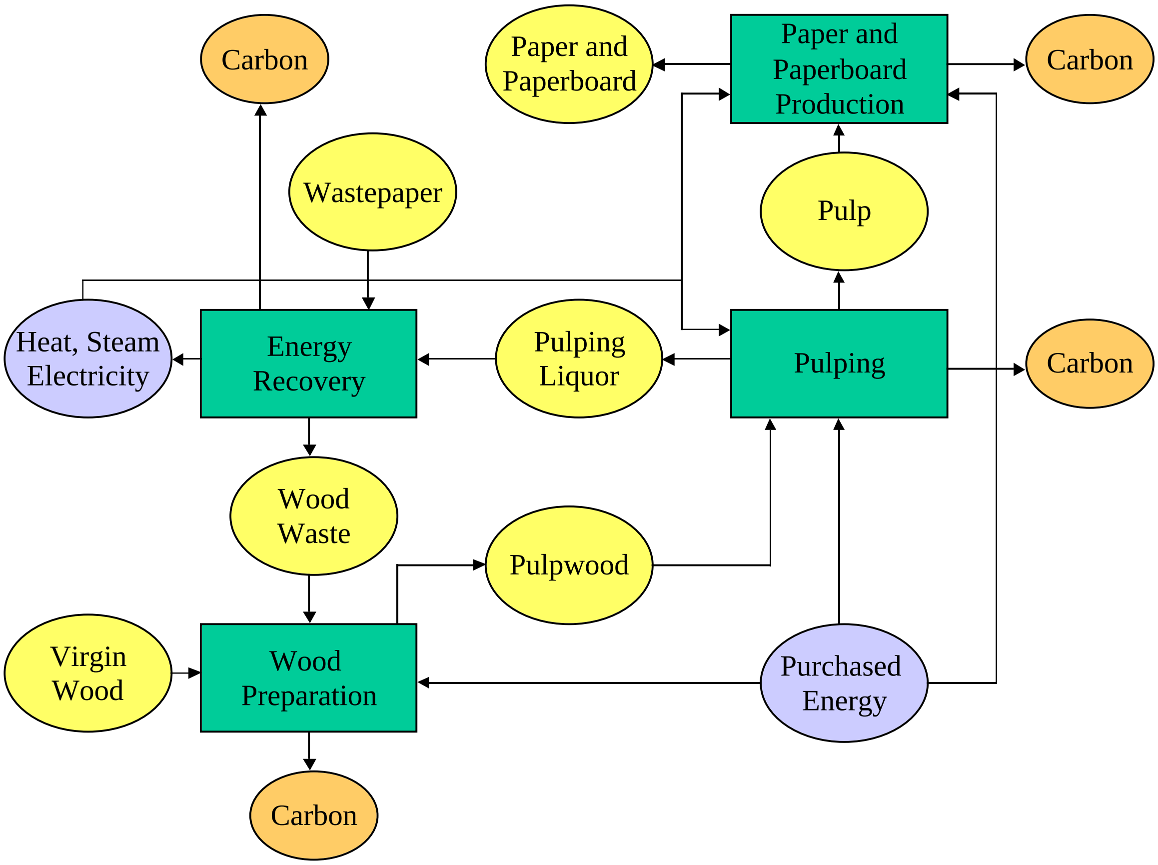

Figure 2. Coke Oven, Blast Furnace and Basic Oxygen Production.

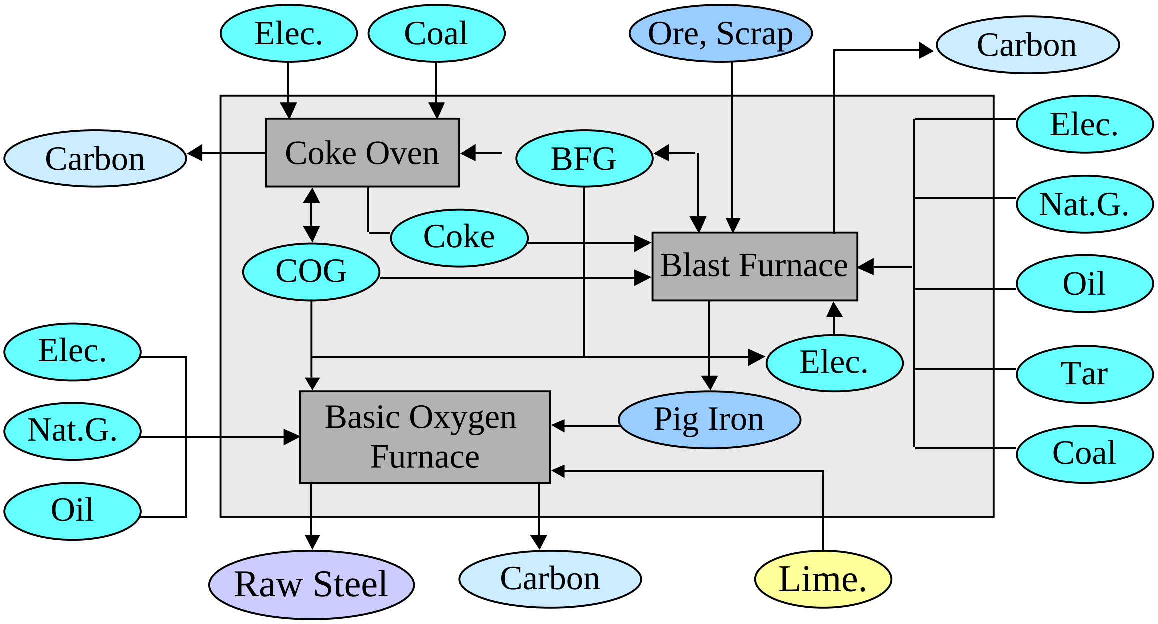

Figure 3. Electric Arc Furnace Production.

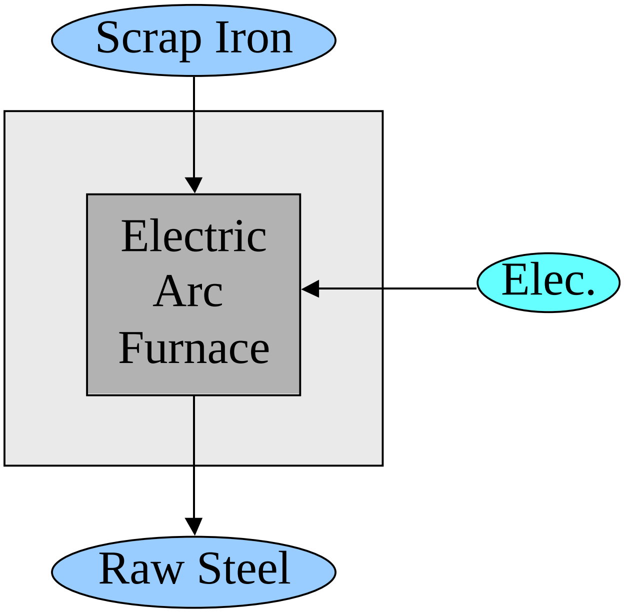

Figure 4. Ethylene Production.

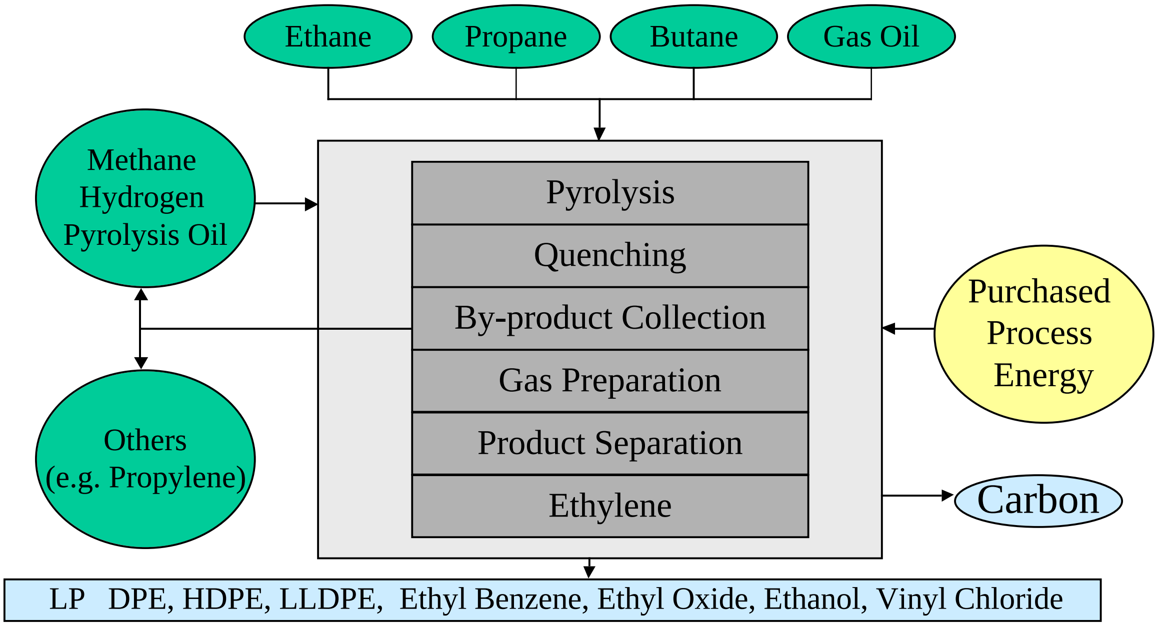

Figure 5: Structure of the Dynamic Industry Models

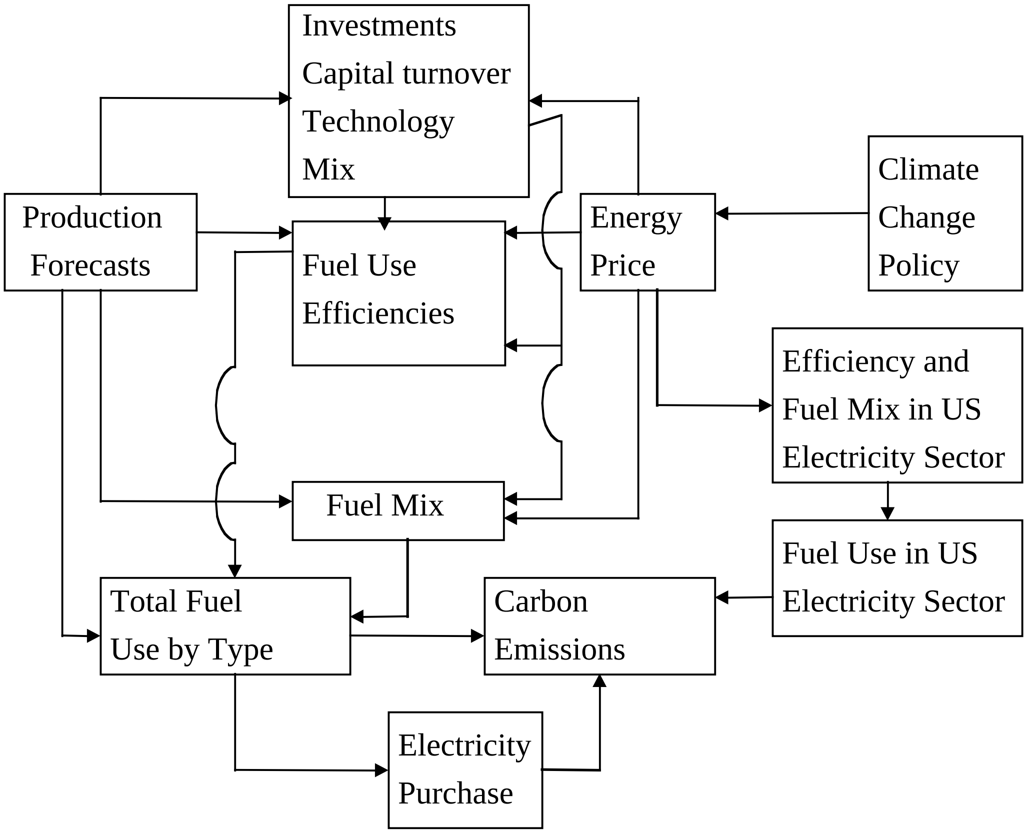

Figure 6. Steel Industry Scenarios with Base Case.

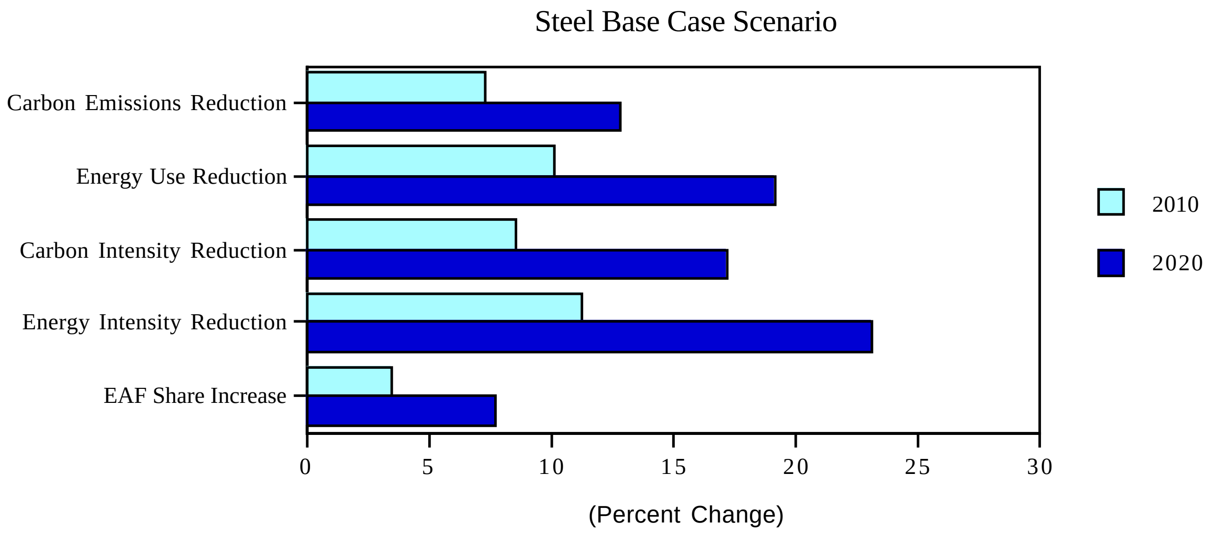

Figure 7. Steel Industry Scenarios with $75 Cost of Carbon.

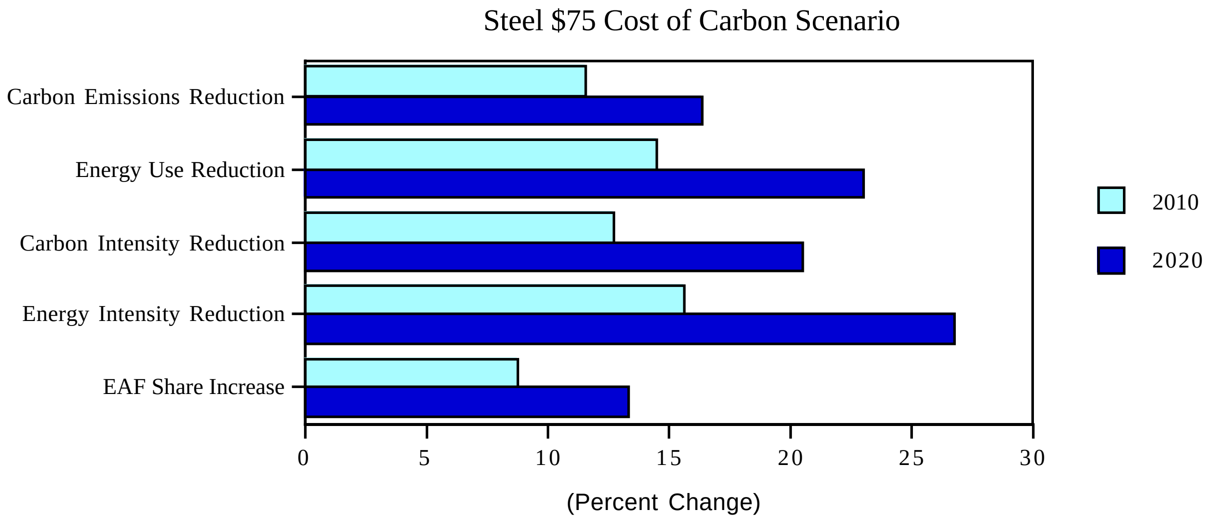

Figure 8. Steel Industry Scenarios with 10% REI Improvement.

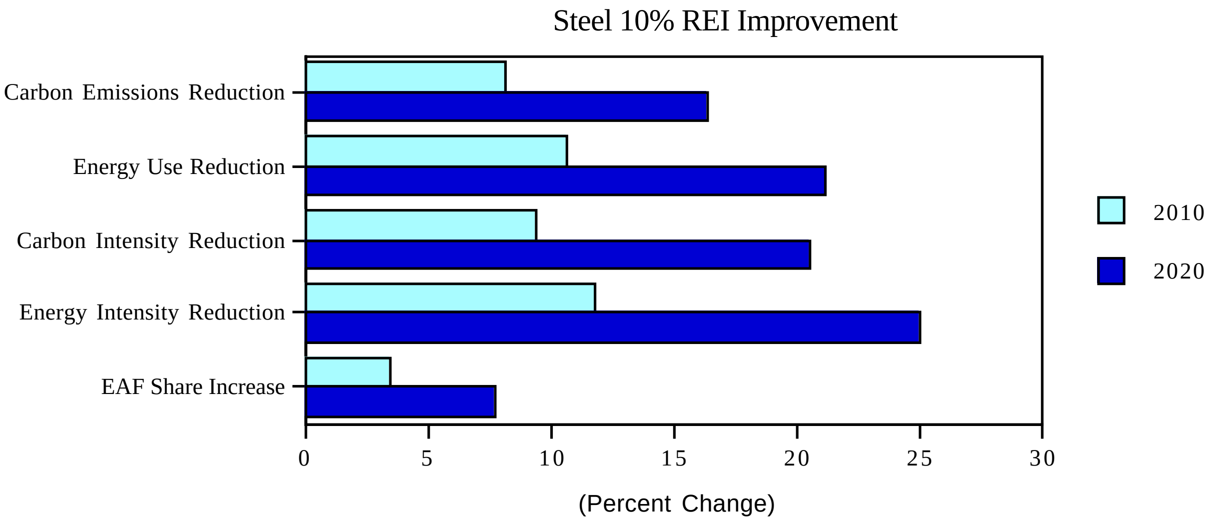

Figure 9. Steel Industry Scenarios with $25 Cost of Carbon & 5% REI Improvement.

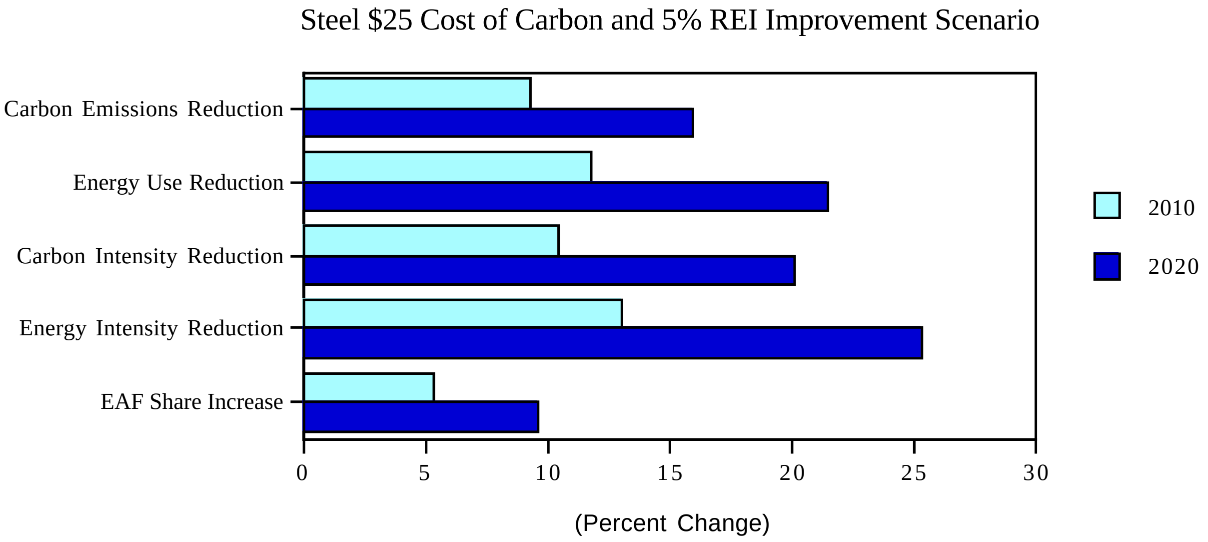

Figure 10. Paper Industry Scenarios with Base Case.

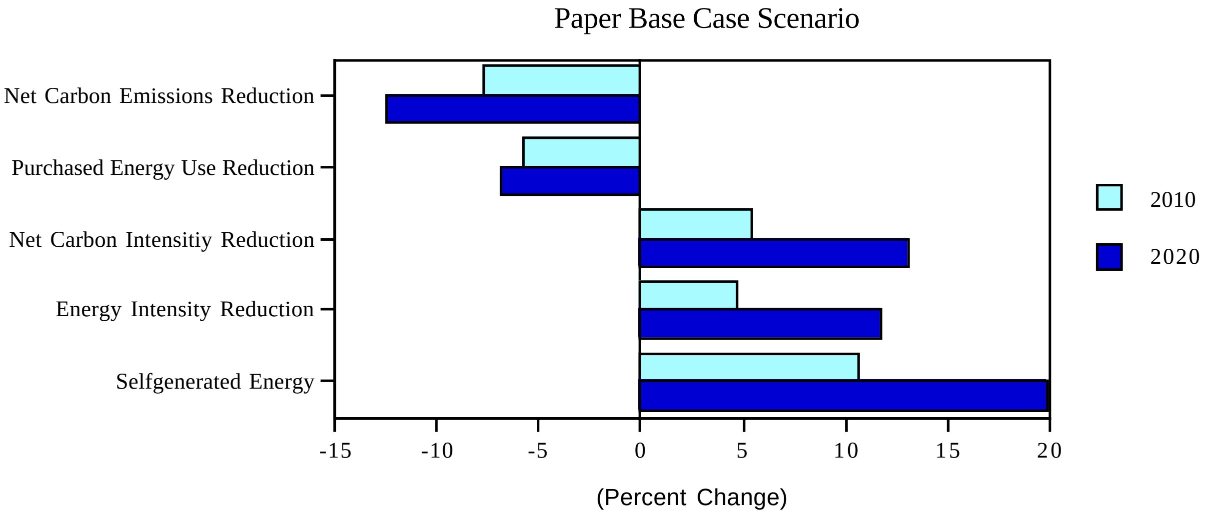

Figure 11. Paper Industry Scenarios with $75 Cost of Carbon.

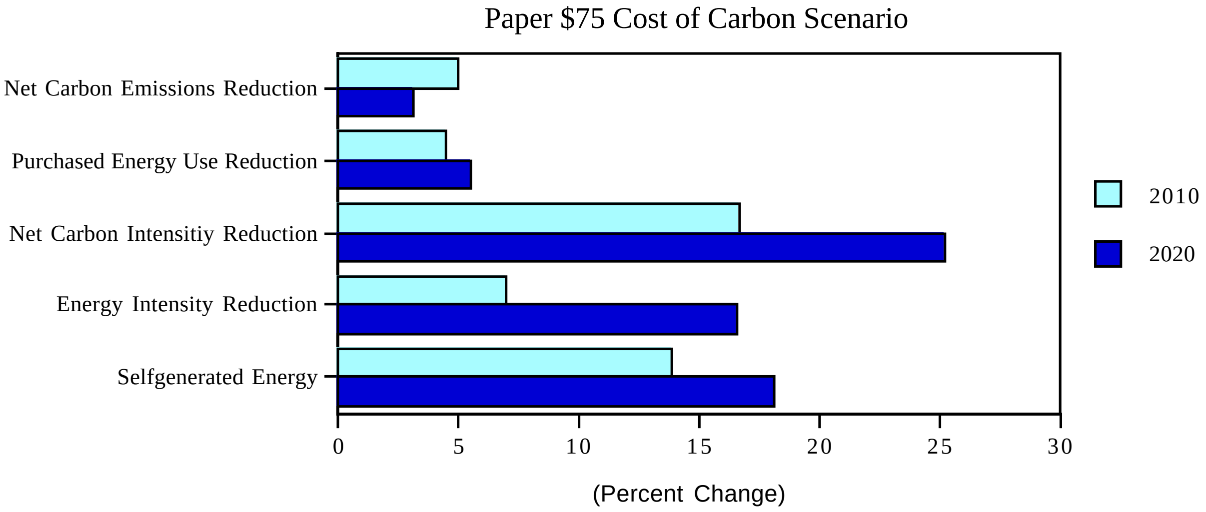

Figure 12. Paper Industry Scenarios with 10% REI Improvement.

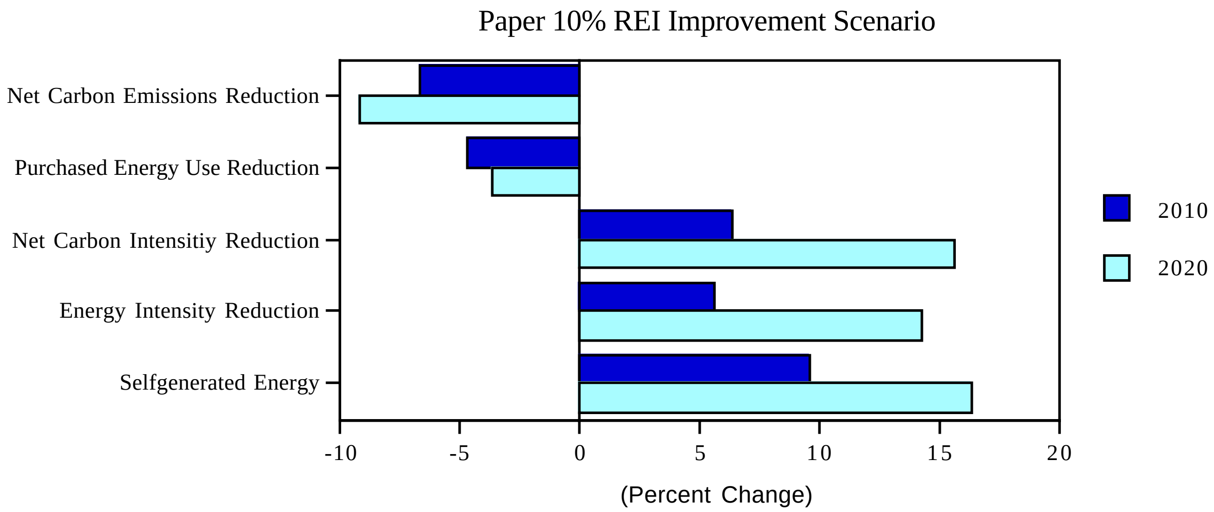

Figure 13. Ethylene Industry Scenarios with $25 Cost of Carbon & 5% REI Improvement.

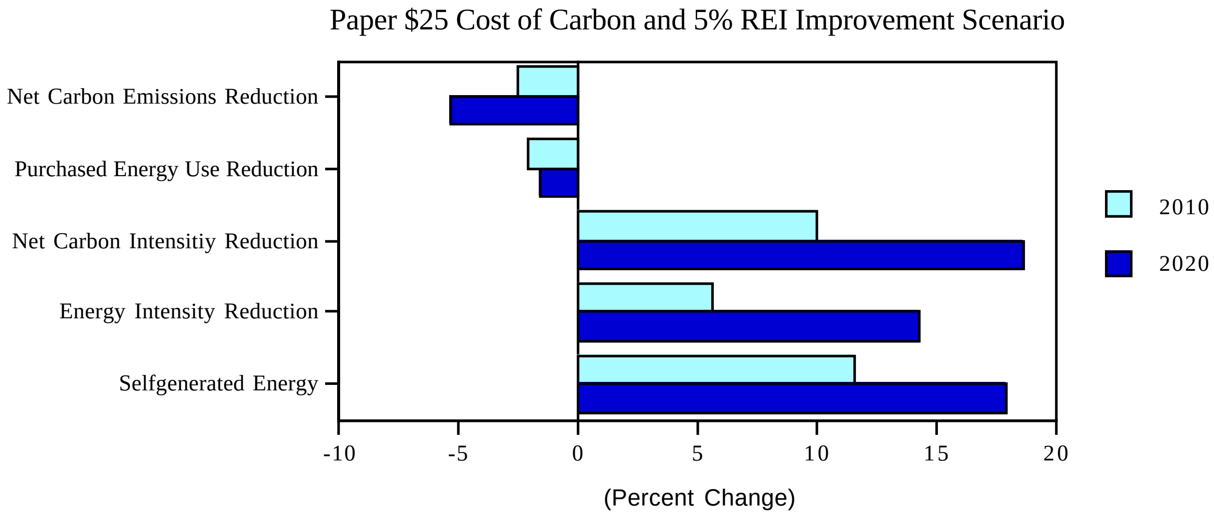

Figure 14. Ethylene Industry Scenarios with Base Case.

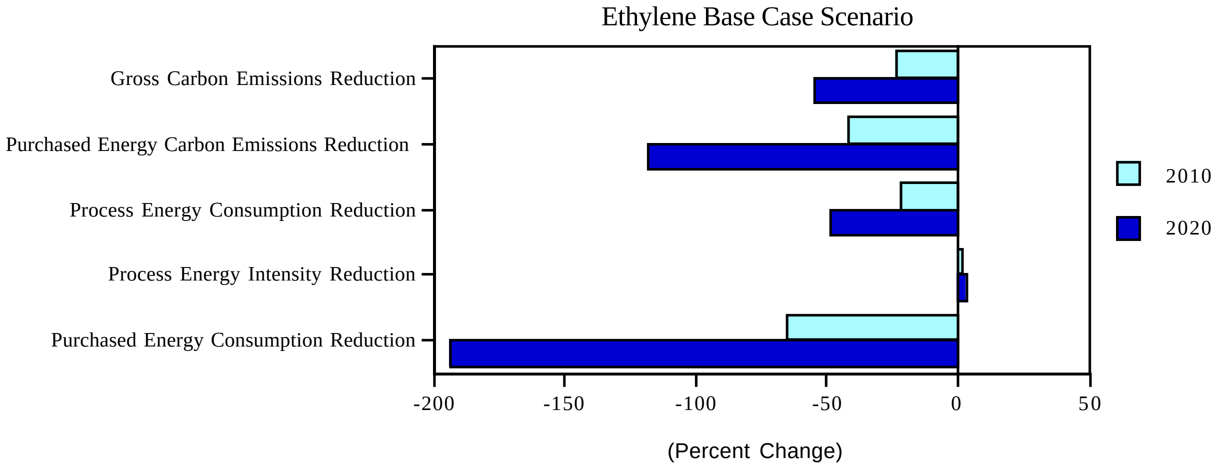

Figure 15. Ethylene Industry Scenarios with $75 Cost of Carbon.

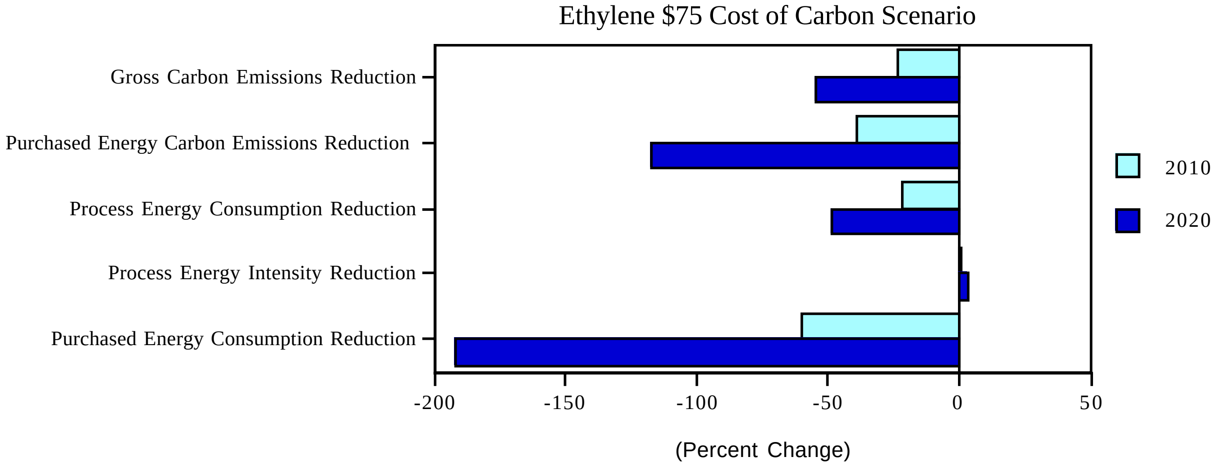

Figure 16. Ethylene Industry Scenarios with 10% REI Improvement.

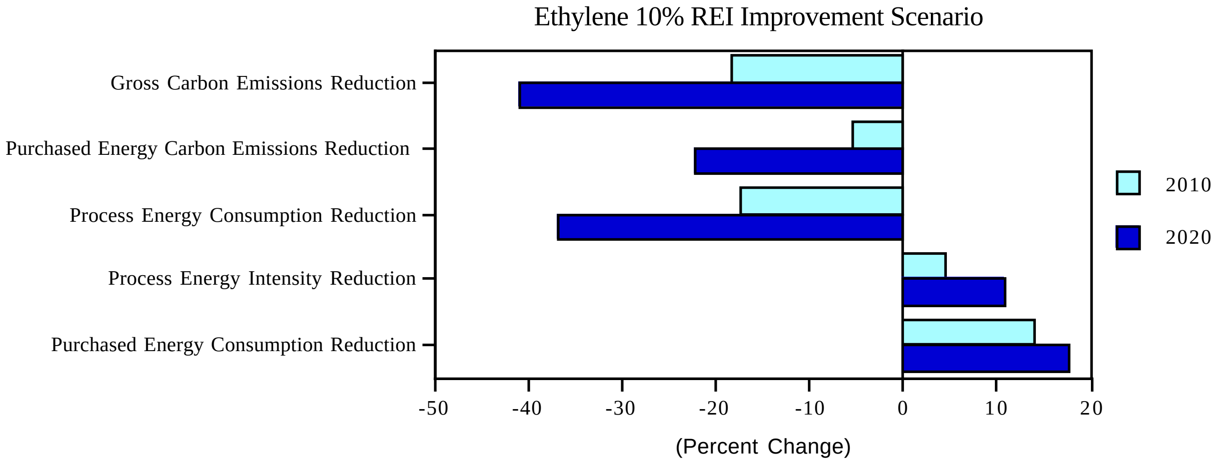

Figure 17. Ethylene Industry Scenarios with $25 Cost of Carbon & 5% REI Improvement.

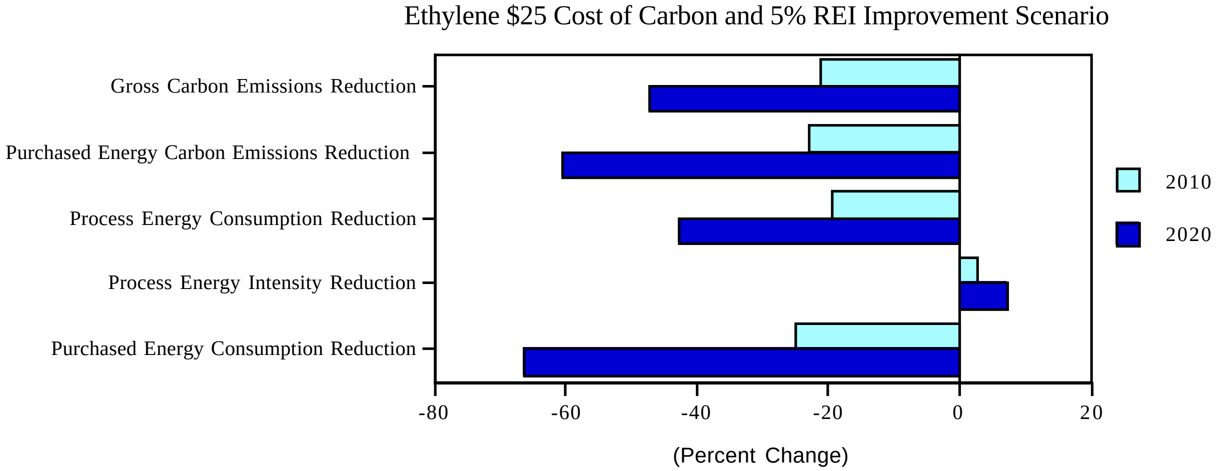

Table 1. Comparison of fixed parameters in the three industry models.

	Pulp and Paper	Iron and Steel	Ethylene
Maximum lifetime of capital (years)	35	20 (EAF)	25
REI	0.85	.96	.96 (Ethane, Naphtha) .976 (Butane, Propane)
Time-lag between investment and actual use of capital (years)	2	1	4
Number of fuel types represented in model	7 (including elec)	6 (including elec)	5 (4 purchased and electricity)

Table 2. Main drivers of change in key endogenous variables.

Endogenous variable	Drivers Pulp and Paper	Drivers Iron and Steel	Drivers Ethylene
Demand	Output prices, GDP/capita	Output prices, GDP, GDP/capita	assumed = supply
Supply	Demand, input prices	Demand, trade-weighted value of dollar	GDP
Gross investment	Input prices, production levels	Output prices, production levels	Capacity utilization, input prices, production
Capital turnover	Fixed fraction of gross investment Lifetime of capital	EAF – lifetime of capital BF – variable retirement rate	Lifetime of capital
Fuel shares	Relative and absolute fuel prices, output mix.	EAF capacity share, relative and absolute fuel prices	Feedstock shares