Carbon Emissions from U.S. Ethylene Production under Climate Change Policies

MATTHIAS RUTH*
Environmental Policy Program, School of Public Affairs,
University of Maryland, 3139 Van Munching Hall,
College Park, Maryland 20742

ANTHONY D. AMATO
Environmental Policy Program, School of Public Affairs,
University of Maryland, 2100 Van Munching Hall,
College Park, Maryland 20742

BRYNHILDUR DAVIDSDOTTIR
Department of Geography, Boston University,
675 Commonwealth Avenue, Boston, Massachusetts 02215

This paper presents the results from a dynamic computer model of U.S. ethylene production, designed to explore implications of alternative climate change policies for the industry's energy use and carbon emissions profiles. The model applies to the aggregate ethylene industry but distinguishes its main cracker types, fuels used as feedstocks and for process energy, as well as the industry's capital vintage structure and vintage-specific efficiencies. Results indicate that policies which increase the cost of carbon of process energy—such as carbon taxes or carbon permit systems—are relatively blunt instruments for cutting carbon emissions from ethylene production. In contrast, policies directly affecting the relative efficiencies of new to old capital—such as R&D stimuli or accelerated depreciation schedules—may be more effective in leveraging the industry's potential for carbon emissions reductions.

1. Introduction

The U.S. chemicals industry accounts for 25% of manufacturing energy use and 2.6% of the country's carbon emissions (*1*). One of the most energy-consuming steps within the chemicals industry is steam cracking of hydrocarbon feedstocks to produce ethylene, propylene, butadiene, and aromatics (*2*). Since the U.S. production of ethylene alone accounts for approximately 28% of world capacity (*3*), technology and policy choice in the U.S. are seen to have far-reaching implications for the industry's contributions to the global carbon cycle. However, even though steam cracking of feedstocks for ethylene production is highly energy intensive, a significantly larger share of the energy used in ethylene production is used as feedstock and ends up in the finished product rather than directly leading to the emission of carbon into the atmosphere. The energy that is combusted during the steam cracking process is used for heating the feedstock, compression, and separation of products.

Ethylene, and to a lesser extent propylene, are the basic components in the production of plastics in the U.S. While they are simultaneously produced from several processes that rely on various feedstocks, each process produces a unique yield of ethylene and propylene, coproducts, and byfuels and requires varying levels of process energy. The amount of process energy use is largely dependent on the choice of feedstock used in the steam cracker. Product yields and process energy use can be varied by technology change and process adjustments. For example, "high severity" cracking, which is performed under higher temperatures and shorter residence times, increases both the yield of ethylene and the amount of process energy required.

Interdependencies among energy, feedstock, technology, and product mix can require complex adjustments by industry to external—market or policy-driven—influences with results that (a) may not be obvious *a priory*, (b) manifest themselves over years, and (c) influence the effectiveness of policy. Many of these interdependencies may be entirely overlooked if one analyzes the chemicals industry as a whole, as is typically done in studies of climate change policy impacts on industry. As a consequence of highly aggregate analysis, policy recommendations may emerge that fall short in promoting technology and environmental improvement. However, disaggregate analyses of policy implications for individual chemicals products suffer from the need to limit technology choices to those that can be well described with publicly available data.

This paper presents a dynamic computer model to organize publicly available data and explore implications of selected climate change policies for feedstock and process energy use of aggregate U.S. ethylene production as well as corresponding carbon emissions. [Only a small set of policies and investment strategies are explored here, compared to the full potential of the model. To receive a copy of the model and explore your own "policy scenarios" send e-mail to mr217@umail.umd.edu.] The paper's purpose is to contrast the effectiveness of policies which increase the cost of carbon of process energy—such as carbon taxes or carbon permit systems—with policies that directly affect the relative efficiencies of new to old capital—such as R&D stimuli or accelerated depreciation schedules.

The paper is organized as follows. Section 2 discusses the system boundaries applied to this study and its underlying methodology. Section 3 presents an overview of data sources and econometric analyses used to specify the model. Section 4 presents model results under a business as usual scenario and compares that scenario to results if alternative climate change policies and investment strategies are chosen. The paper closes with a brief summary and conclusions. Technical details can be found in the Supporting Information.

2. System Boundaries and Methodology

The ethylene model traces for each individual cracker type (ethane, propane, naphtha, and butane) the flow of fuels used as feedstocks, byfuels from ethylene production, and purchased process energy required to produce ethylene (Figure 1). Since information on the industry's process energy use is not directly available, we use industry cracker efficiency estimates along with historic production data to deduce the industry's total energy use. From information on energy use we calculate annual carbon emission rates on the basis of historical data until the year 1998 and then project energy use and carbon emissions profiles until the year 2020. The model also traces indirect carbon emissions associated with the generation of purchased electricity but does not trace

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* Corresponding author. Email: mr217@umail.umd.edu Phone: 301-405-6075 Fax: 301-403-4675.

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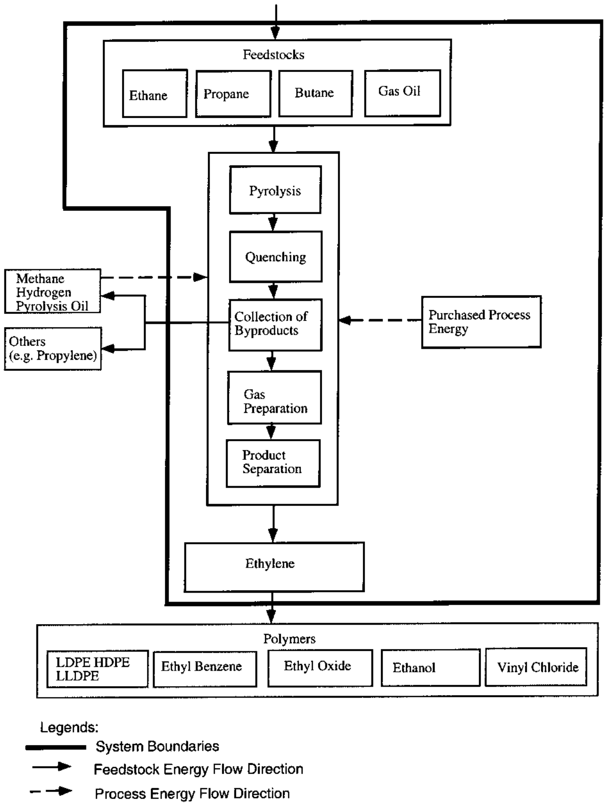

FIGURE 1. System components and boundaries.

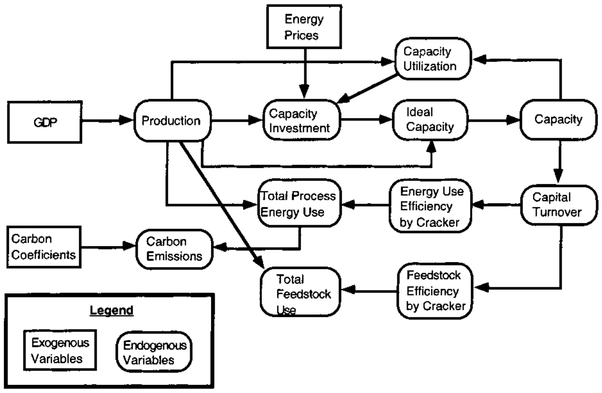

FIGURE 2. Model configuration.

energy used to produce final products from ethylene. Carbon emissions as a result of processes outside of the ethylene production process itself, such as the downstream production of plastics from ethylene or the incineration of ethylene end products during waste disposal, are not accounted for by the model.

The key exogenous drivers to the model include historic and forecast energy prices, GDP, and fuel-specific carbon coefficients. Each of these drivers, plus many of the functional relationships, can be interactively adjusted in the model to investigate alternative futures for the industry, making the model a versatile tool for investment and policy analysis of the U.S. ethylene industry. Given assumptions about exogenous drivers, the model endogenously calculates production rates, capacity and investment requirements, efficiency changes, energy and feedstock use, and carbon emissions as the result of interactions among the many different components of the industry (Figure 2). Endogenous calculations are based on econometric estimates and engineering information described in the next section and presented in more detail in the Supporting Information.

A key feature of the model lies in its explicit representation of the industry's capital vintage structure. The capital vintage description of the model follows the perpetual inventory methods pioneered by Jorgenson (*4, 5*). In that model, the end-of period capital stock is estimated as a function of gross new capital investments (I_t), existing capital stock (K_{t-1}), and rate of replacement (μ), where all variables are measured in monetary units:

$$K_t = I_t + (1 - \mu)*K_{t-1}$$

We modify Jorgenson's approach by creating a physical perpetual inventory. We do this by estimating the physical size and vintage structure of the capital stock in the most recent year available. The future size and structure of the capital stock is then estimated as a function of gross new capital investments—translated into new physical production capacity—and the size of the existing physical capital stock minus the retirement of physical capital. In our adaptation of this approach for the U.S. ethylene industry, information on annual changes in capital stock is used to calculate production capacity, giving an estimate of the age structure of U.S. capacity to produce ethylene in physical units. Parallel to the capital stock's age structure the model traces a set of age-specific efficiency characteristics by production process.

Changes in efficiency occur through the replacement of old, retiring capital with new, more efficient capital. The changing capital vintage structure gradually increases overall efficiency of the industry and reduces the intensity of feedstock and/or of process energy use of new capital relative to existing capital stock in that year. Aggregate efficiency of the ethylene industry is calculated as a weighted sum of vintage-specific efficiencies of all processes, where the weights are determined by production capacity of the respective vintage class used in each process. The model assumes that within a vintage class efficiencies remain constant and that each capital vintage class is fully retired after 25 years.

We explicitly trace the industry's capital stock for two main reasons—one theoretical, one practical. First, a growing number of industry-specific economic analyses place emphasis on the role that capital vintage effects play for firms' input choice, rate of technology change, and environmental performance (*6*−*9*). Theoretical work dating back to Leontief (*10*), Fisher (*11*), and Diewert (*12*) explores conditions under which an aggregate capital stock can be defined and emphasizes the relevance that relative efficiencies of capital of different vintage classes do have for that definition (*13*).

Second, capital vintage effects have also been associated with technology lock-in (*14*), which may impede rapid reductions of carbon emissions. The lock-in hypothesis posits that incremental development of a firm's knowledge base over time produces standard operating procedures that can be barriers to the adoption of new technologies. In addition, since capital investments are generally financed from a firm's own cash flow, internal investments tend to strengthen existing production processes and products. Thus, as a firm grows older it may become less inclined to update its technologies and as a result closely follows a specific technology trajectory. Under some conditions initial technology choices may gradually rigidify and lock in potentially inefficient processes. Developments at the firm level may be accompanied, and even exacerbated, by lock-in of institutions that oversee or regulate an industry (*15*).

The role of industrial capital vintage structure in influencing future investment choice and effectiveness of climate change policies has led to calls for more detailed representations of capital vintage structures in models for investment and policy analysis (*16, 17*). The explicit representation of the industry's capital vintage structure in our study enables us to elucidate the implications of a wider range of policies for carbon emissions, such as policies that are expressly targeted toward development and adoption of advanced technologies, instead of simply dealing with policies that raise the cost of energy or carbon.

3. Data Sources and Econometric Analysis

The model components of Figure 2 and their interrelationships are specified on the basis of historical data and engineering information. All resulting equations are solved simultaneously with the use of a dynamic computer model specifically designed to handle large numbers of simultaneous difference equations which may contain time-lags and nonlinearities (*18*, *19*). The model is calibrated over historic time (1970−1998) and run to explore future trajectories until the year 2020.

Parameter estimation techniques chosen for model specification include multivariate regressions using both simultaneous and lagged independent variables as well as seemingly unrelated regressions. Model (parameter) specification is based on conventional hypothesis tests (t, F-test, and R^2) as well as extensive econometric diagnostics such as Lagrange multiplier tests for heteroscedasticity (*20*) and serial correlation (*21*). Estimation results as well as basic engineering information on the relative intensity of feedstocks and process energy, feedstock shares and ethylene yields, purchased process energy use, and carbon contents of fuels are provided in the Supporting Information.

4. Scenario Analysis and Results

4.1. Base Scenario. It is the purpose of the model to explore likely trajectories for process energy use and carbon emissions under business as usual scenarios—assuming continuation of trends embedded in the time series data—and to compare these trajectories to those that would result under alternative climate change policies. The goal of such a comparison is the identification of effective leverage points for policy and investment decisions to influence carbon emissions from ethylene production. While the model is based on a set of simplifying assumptions, many of which are the consequence of insufficiently disaggregated, publicly accessible industry data, it performs well in tracking historic trends and clearly suggests the extent to which alternative policies affect process energy use and carbon emissions from the production of ethylene.

The base scenario assumes that no new policies are implemented and that new capital is 4% more efficient than the industry's aggregate existing capital stock producing different efficiencies for vintage classes. For example, in the year 2020 the gap between ethane crackers just coming on line and those about to be retired is 7.2%. While this efficiency gap is not large, it is consistent with the trends in the broader chemical industry where improvements in energy efficiency have remained relatively flat since the late 1980s (*22*).

Ethylene output—specified as a function of GDP—reaches almost 83 billion pounds by 2020 in the base scenario. Total process energy use—including byfuels produced during production—increases by 109% between 1990 and 2020, while the total purchased process energy use increases by 433%. The reason for this difference is that processes that are more efficient at producing ethylene are less efficient in the production of byfuels. Reduction in byfuel production results in an increase in the use of purchased process energy. However, we must note that purchased process energy accounted in 1990 for only 1.6% of total process energy use in the ethylene industry. We expect process energy use per million pounds of output to decrease by 9% between 1990 and 2020. Over the same time frame, purchased process energy use per million pounds of output is expected to increase by 132% due to reasons detailed above.

When excluding carbon from byfuel combustion, carbon emissions from ethylene production increase by 245% between 1990 and 2020. When carbon emissions from byfuel combustion are factored in, carbon emissions increase by 120% between 1990 and 2020. When we contrast these trends with an expected increase of 50% in carbon emissions (net of emissions from byfuels) *per million pounds of product* over the same time frame, it becomes apparent that byfuel production is a crucial determinant for the industry's carbon emissions profile and that technology change occurs at faster rates than output increases—even in the absence of new policies.

4.2. Policy Scenarios. To explore potential impacts of different climate change policies on energy use and carbon emissions we choose alternative policy scenarios that we assume to be implemented in the year 2004. Several leverage points for policy exist to affect carbon emissions from ethylene production. One strategy is to raise the cost of purchased process energy on the basis of the carbon content of fuels in hopes of stimulating energy savings and thus emissions reductions. Another strategy is to directly stimulate development and diffusion of more energy efficient technology, for example, by boosting research and development of new equipment and providing tax or other incentives to industry to more rapidly adopt such equipment.

A cost of carbon increase is explicitly modeled as a price-adder for fuels, where the magnitude of the adder depends on the fuels' carbon content. Effects of technology-directed policies are captured implicitly by decreasing the intensity of process energy of new capital relative to the process energy intensity of the existing capital stock (the so-called relative process intensity—RPI). The effects of these and similar strategies can be explored in the model in isolation from each other or in various combinations. However, each scenario must assume that the structure of the industry remains unchanged (i.e. no fundamentally new feedstocks or technologies emerge to produce ethylene, capital equipment has at the most a 25-year lifetime, and markets for inputs and products continue to be competitive) and that producers do not foresee the advent of new policies. Allowing the model to capture fundamental changes in the industry's production processes would require specification of those processes in terms of their fuel mix and energy and feedstock efficiencies. Where such descriptions exist they can be readily used to respecify the model. Given the capital-intensity of the ethylene industry, new technologies will take time to diffuse. If new capital stock were needed to handle, e.g., biomass feed (ethanol, methanol) or to conduct back-to-polymer recycling, the associated changes—in the ethylene industry aggregate—would not be felt for some time. In contrast, technologies such as gas-turbines placed in front of the cracker (turbine off-gases with temperature of 500 °C are used in the burners instead of combustion air) do not require that the capital stock has turned over and can be added to the existing stock and thus more readily influence efficiencies. Similarly, the use of new catalysts by ethylene producers could lower energy consumption by 20% (*23*) without requiring major turnover of the existing capital stock. In reality, increased energy prices could make investments into such technologies cost-effective.

Changing the assumption that the maximum lifetime of capital equipment is 25 years seems mute in light of historical trends in the industry. Allowing the model to accommodate changes in market structures and producer expectations would require, for example, game-theoretic approaches that describe economic behavior under alternative market conditions and behaviors of industry decision makers. To date, too little well-grounded information is available to pursue that line of research for the ethylene industry.

TABLE 1. Summary of Model Results

	base scenario	$75/ton carbon	RPI 0.940
total production (% change from 1990 levels to 2020)	130.1	130.1	130.1
total purchased energy use (% change from 1990 levels to 2020)	432.6	428.5	348.6
total process energy use (% change from 1990 levels to 2020)	108.7	108.8	107.4
total process energy use per output (% change from 1990 levels to 2020)	−9.3	−9.2	−9.8
total purchased process energy use per output (% change from 1990 levels to 2020)	131.5	129.7	95.0
years gained in efficiency improvement		0	3
gross carbon emissions (% change from 1990 levels to 2020)	120.3	120.2	118.4
net carbon emissions (% change from 1990 levels to 2020)	244.5	242.9	211.4
net carbon emissions per ton of output (% change from 1990 levels to 2020)	49.8	49.1	35.3
Financial Parameters			
cumulative present value of energy expenditures for purchased process energy, 2000−2020 (billion 1994 $, 5% discount rate)	1.343	1.549	1.320
cumulative present value of cost of carbon payments, 2000−2020 (million 1994 $, 5% discount rate)	0	201.1	0
energy expenditures purchased process energy in 2020 (net of cost of carbon, where applicable) (million 1994 $)	112.7	112.2	102.2
cost of carbon in 2020 (million 1994 $)	0	45.632	0
energy cost per unit of output in 2020 (1994 $/short ton output) (net of cost of carbon, where applicable)	1.343	1.337	1.217

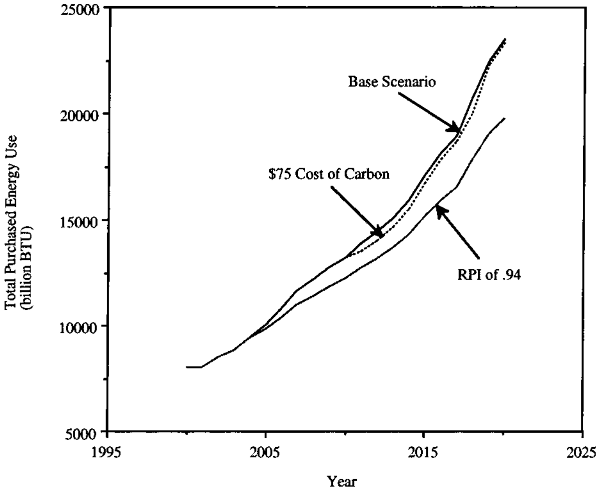

FIGURE 3. Purchased process energy use with and without climate change policies.

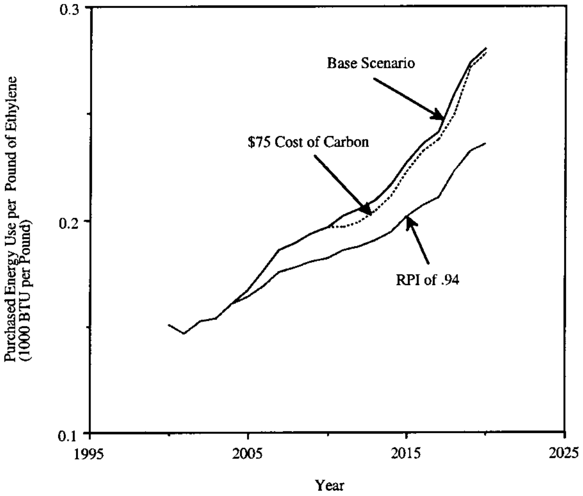

FIGURE 4. Purchased process energy use per pound of output with and without climate change policies.

Given the prescribed structure of the industry and available technologies, the following discussion contrasts a cost of carbon policy with policies that improve the relative process intensities of new to existing capital (RPI). Results indicate that reducing RPI marginally (from 0.960 to 0.959) achieves the same total carbon emissions in 2020 as a $75/ton increase in the cost of carbon. A slightly more ambitious improvement in RPI from 0.960 to 0.940 leads the industry to achieve an approximately 20% reduction in carbon emissions by 2020 over those in the base scenario and the same aggregate energy efficiencies in the year 2017 as would be achieved with an RPI of 0.96 in the year (cf. Table 1).

The model indicates that if cost of carbon or RPI-directed policies are implemented, purchased process energy use—both total and per unit output—continue to increase over time but at a lower rate than in the base scenario (Figures 3 and 4 and Table S-5 (Supporting Information)). The reason for the difference in the impact of an increase in the cost of carbon on purchased process energy compared to the impacts of policies affecting RPIs is due to the different ways in which these policies would influence the relationship between investment and the production of byfuels. If, for example, investment in energy efficient capital declines because of lower energy prices, the rate of improvement in both feedstock energy efficiency and process energy efficiency declines as well. This in turn causes an increase in byfuel production, triggering a decline in the use of purchased process energy.

Carbon emissions from purchased process fuels (excluding emissions from byfuel combustion) will continue to increase but will increase less rapidly than in the base scenario (Figure 5). The same trend can be seen for carbon emissions from purchased process fuels (excluding emissions from byfuel combustion) per million pounds of output (Figure 6).

5. Discussion

This paper presents selected results from a dynamic computer model of U.S. ethylene production, specified on the basis of historic data, engineering information, and forecasts of GDP and energy prices. The purpose of the model is to highlight key leverage points for policy or investment decisions which have the goal of reducing the industry's carbon emissions through process efficiency improvements. Specific attention is given in our model to the industry's capital vintage structure and the efficiencies of existing and new capital equipment in using feedstock and process energy. An important

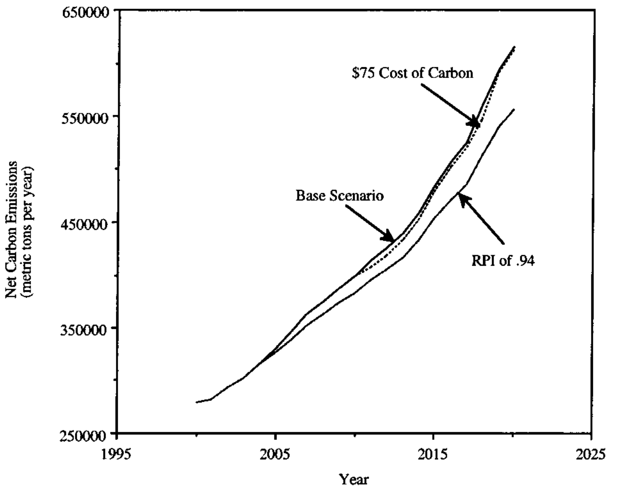

FIGURE 5. Carbon emissions from purchased process energy with and without climate change policies.

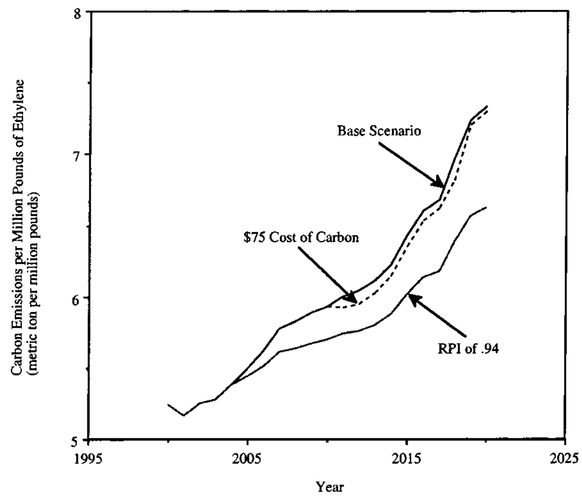

FIGURE 6. Carbon emissions from purchased process energy per million pounds of output with and without climate change policies.

distinction is made between purchased process energy and process energy from byfuels.

Though this and any other publicly available study of the ethylene industry are severely hampered by the lack of industry-specific energy and emissions data, no assessment of alternative policies will ever have all the data it needs. But herein lies the beauty of dynamic modeling—an ability to build on the best available data and to explore the likely consequences of alternative assumptions. As the ethylene model above shows, those consequences are fairly distinct if policy increases the cost of carbon or directly affects the turnover of capital in favor of more efficient equipment.

Our results indicate that increasing the cost of carbon for the ethylene industry produces only small changes in carbon emissions due to the structure of the industry. Almost all fossil fuels purchased by the industry are incorporated into the product itself as a feedstock. If the cost of carbon is increased only for fossil fuels that provide process energy, the industry has little incentive to change its behavior since these fuels are only a small percentage of total monetary outlays. Energy efficiency will largely be determined by feedstock choice, which in turn remains based on market demand for ethylene and its coproducts. To induce significant changes in the energy profile of the industry, changes in the capital stock need to occur. For example, the integration of gas turbines can lead to further improvements in energy efficiency by lowering fuel requirements to the heater (*24*).

Our results from policies aimed at increasing the cost of carbon for purchased process energy show limited potential for emission reductions. However, if the cost of carbon is increased not only for purchased process energy but also for fuels used as feedstock, then significant reductions in greenhouse gas emissions (GHG) may result. For example, Greonendaal and Gielen (*25*) find for the European chemical industry that increased GHG permit prices for all fuels has the potential to significantly reduce emissions by 2030. Emission reductions are found to be largely due to a shift from fossil fuel-based to biomass-based feedstocks, which have no net emissions, and to a lesser extent the recycling of waste plastics by consumers. A comparison of model results demonstrate that industrial emissions' profiles are highly sensitive to assumptions about how broadly cost of carbon policies are applied to fuel inputs and what system boundaries are chosen for emissions accounting.

Introducing performance goals or technology standards can produce noticeable changes in process and purchased energy use and thus carbon emissions. Performance goals or technology standards—collectively reflected in our model as impacting relative process energy intensities of new to old capital (RPIs)—may be the product of voluntary or government-led actions but will be most effective if they stimulate provision of highly efficient capital to industry and lead to an efficiency gap between new and existing capital for industry to close. While there are clear long-term technological and thermodynamic limits on efficiency of new capital, intensified R&D and technology adoption, combined with disproportionally higher utilization rates of newer rather than older capacity, can go a long way in establishing and then exploiting the efficiency gap. Investment tax credits and accelerated depreciation schedules are but two examples that could help leverage the effectiveness of performance goals and technology standards. The study results clearly indicate that such policies are more effective than mere increases in the cost of carbon in cutting carbon emissions.

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Supporting Information Available

Key functional relationships, econometrically estimated parameters, and engineering information used in the dynamic, capital vintage model of U.S. ethylene production. This material is available free of charge via the Internet at http://pubs.acs.org.

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