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Long-Term US Industrial Energy Use and CO2 Emissions

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Abstract

We present a description and scenario results from our recently-developed long-term model of United States industrial sector energy consumption, which we have incorporated as a module within the O^{bj}ECTS-MiniCAM integrated assessment model. This new industrial model focuses on energy technology and fuel choices over a 100 year period and allows examination of the industrial sector response to climate policies within a global modeling framework. A key challenge was to define a level of aggregation that would be able to represent the dynamics of industrial energy demand responses to prices and policies, but at a level that remains tractable over a long time frame. In our initial results, we find that electrification is an important response to a climate policy, although there are services where there are practical and economic limits to electrification, and the ability to switch to a low-carbon fuel becomes key. Cogeneration of heat and power using biomass may also play a role in reducing carbon emissions under a policy constraint.

1. Introduction

This paper presents a new, long-term model of US industrial sector energy consumption implemented within the O^{bj}ECTS-MiniCAM long-term integrated model of the global energy system. Our methodology and our selection of an appropriate level of industry and end-use technology aggregation is described. A reference case of future US industrial energy and emissions is developed. The paper concludes with a scenario analysis of the potential technology and fuel choice response of key energy end-uses under a CO$_2$ emissions reduction policy.

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This new development is part of a long-term effort to implement detailed descriptions of energy-technologies for the major end-use sectors: industry, buildings (Clarke *et al.*, 2007), and transport (Kim *et al.*, 2006). Because it must function as part of the larger, integrated model, our approach to developing a detailed industrial sector module requires a balance between completeness and complexity in the degree of detail necessary to represent the critical trends, processes, technologies and fuel choices that may play a part in industrial sector energy consumption and greenhouse gas emissions over the next 100 years. Consequently, our modeling makes no attempt to replicate all of the detail and the analytical capabilities in detailed industrial models. Instead, our goal is to continue to improve our long-term integrated modeling so that climate policy analysis reflects realistic constraints and technological opportunities within sectors, all while providing unique insights through integration and feedback with the rest of the global energy system.

1.1 Approaches to Modeling Industrial Sector Energy

Compared to other parts of the energy system, the industrial sector is heterogeneous and complex. A broad community of experts in industrial energy, as well as a community of detailed industrial energy models, has developed over the last few decades. Recently, the journal *Energy Economics* has published a special issue on industrial energy modeling, providing an overview of the state of the art (Greening *et al.*, 2007). Many of these models include very specific process-level technology detail. We discuss just a few of those models here. At the other extreme are long-term, integrated assessment models of the global energy and related systems, which have a very aggregate representation of industrial energy. MiniCAM belongs to this family of models, which we will also discuss in order to place our new industrial work in that context as well.

The Consolidated Impacts Modeling System (CIMS) and the MARKet ALlocation model (MARKAL) are two prominent examples of models developed for studying the effects of specific industrial (as well as other energy sector) technologies, as they contain specific data thousands of industrial energy and process technologies. The CIMS model was developed by the Energy and Materials Research Group at the Simon Fraser University in British Columbia, Canada. Parts of this model are based on a version of the Industrial Sector Technology Use Model (ISTUM) developed by the Pacific Northwest National Laboratory for the US DOE. CIMS has been used to examine the industrial response to climate policy in Canada (Murphy *et al.*, 2007). A CIMS-US has also been built (Roop, 2006). Although CIMS was constructed with bottom-up detail, it can be considered a hybrid model as it does contain equilibrium feedbacks to the macro-economy (Bataille *et al.,* 2006).

The MARKAL model uses a bottom-up process-engineering approach to represent the industrial sector, along the rest of the energy system. Among other advancements to the US-MARKAL, the Los Alamos (LA-MARKAL) version expanded the technology choice set to over 4500 technologies which makes it the most detailed model for the US. (Greening, 2006). In contrast to the behavioral simulation of CIMS, this model uses a dynamic linear programming framework to solve for the minimum cost energy system solution. The time horizon for the LA-MARKAL is from 1995 to 2100. LA-MARKAL can also be considered a hybrid model as its bottom-up depiction of the energy system contains links to the macro-economy. In addition to the LA-MARKAL implementation, several other groups have implemented their own versions of MARKAL around the world.

The National Energy Modeling System (NEMS) of the US Energy Information Administration (EIA) contains a fairly detailed industrial sector module. The NEMS industrial sector is more similar in aim to our goals as it is developed to fit within the larger modeling framework of the NEMS, and has to balance its level of detail in that context. The NEMS industrial sector was primarily designed to forecast mid-term (on the order of a few decades) industrial energy consumption by energy source for 21 manufacturing and 6 non-manufacturing industries. Among the manufacturing industries, the energy-intensive industries are modeled using process flow and the non-energy-intensive industries are represented by their end use energy consumption. This model can also be used to study the effect of different environmental and regulatory policies, but it can also be used to analyze technology programs, though perhaps in less detail than CIMS and MARKAL (EIA, 2005b).

As stated, our development of MiniCAM makes no attempt to replicate, much less improve, on the level of detailed industrial energy modeling in these models. Instead, we attempt to improve the representation of industrial energy modeling in a long-term, integrated assessment (IA) model used for global energy and greenhouse gas analysis. For context, consider the three IA models used for the US Climate Change Science Program (CCSP) scenario analysis project (Clarke *et al.*, 2007): the MIT EPPA model (as part of IGSM), the MERGE model, along with the MiniCAM model.[1] These models all consider the global energy system on a century scale or longer. In terms of industrial sector detail (at the time of the CCSP analysis), MERGE aggregates all final demand sectors into a single non-energy sector. MiniCAM did distinguish industrial energy from buildings and transportation, but with a single aggregate industrial sector for each region. EPPA went a bit further as it separated an energy-intensive energy sector from other industries. However, none of these CCSP models, MiniCAM included, could provide much insight into the role of specific industrial technologies in contributing to or mitigating future emissions of greenhouse gases.

1.2 The MiniCAM Model, and our General Approach

The design strategy for the MiniCAM model, a long-term global integrated assessment model for global change analysis is to incorporate realistic dynamics of each portion of the climate-energy-economic-agricultural system, but at a level of detail that is transparent and manageable in a 100-year modeling context (Edmonds *et al.*, 2004). The new industrial model embeds a service-based representation of industrial energy demands within this global, partial-equilibrium modeling framework. The model is implemented within the Object-oriented Energy and Climate Technology Systems (ObjECTS) Framework, an object-oriented framework that allows us to include explicit, bottom-up technology details while maintaining the long-term global and regional economic context necessary for understanding global change. This modeling strategy, which can be referred to as a "hybrid" approach between "top-down" and "bottom-up" modeling strategies, is facilitated by the adoption of object-oriented programming techniques (Kim *et al.*, 2006).

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[1] The Emissions Prediction and Policy Analysis (EPPA) model is maintained by the Massachusetts Institute of Technology and is a component of the Integrated Global System Model (IGSM). MERGE was developed jointly by Stanford and the Electric Power Research Institute.

We begin here with an overview of US industrial energy consumption and CO_2 emissions, and we discuss the main drivers of emissions and potential sources of future emissions mitigation. We then discuss our modeling approach and data sources. We finish with an analysis of the impact of a hypothetical global CO_2 emissions policy on the US industrial sector, highlighting insights gained by linking this level of industrial sectoral detail with our global integrated model.

2. US Industrial Sector Energy Use and CO_2 Emissions

The industrial sector spans an enormous and heterogeneous range of individual industries. Energy consumed to produce goods ranging from food products, furniture, petroleum, automobiles, and computers is all considered under the broad definition of industrial sector energy consumption. US total industrial energy consumption is currently comparable to its value 30 years ago (Figure 1). With the economic growth that has occurred over those decades, the energy intensity of US industrial sector relative to the overall economy has been declining. However, energy use in some energy-intensive industries such as Chemicals and Petroleum Refining (Figure 2) has been growing rapidly over the last two decades.
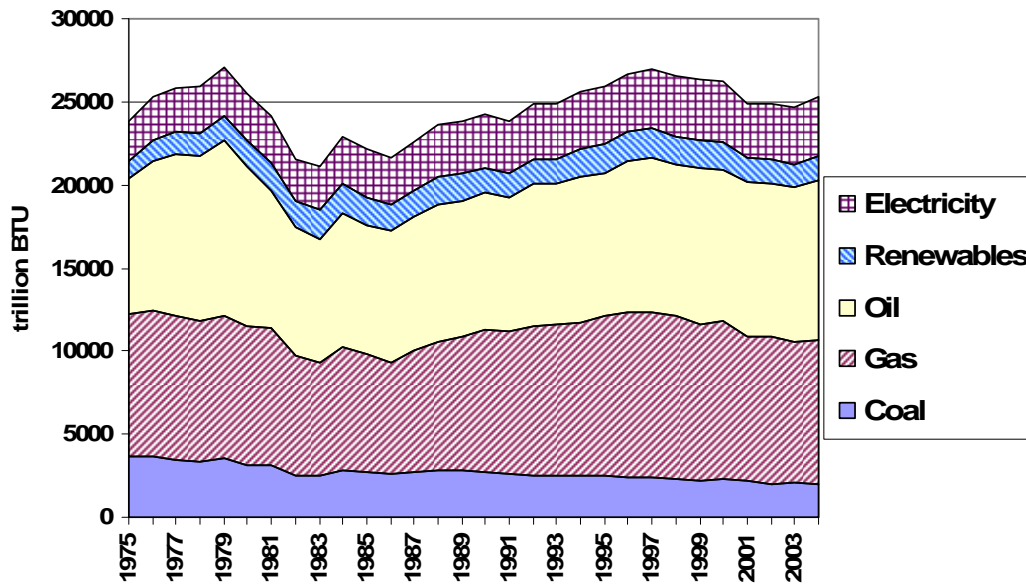

Figure 1. US Industrial Annual Energy Consumption, by fuel (Source: EIA, 2005a)
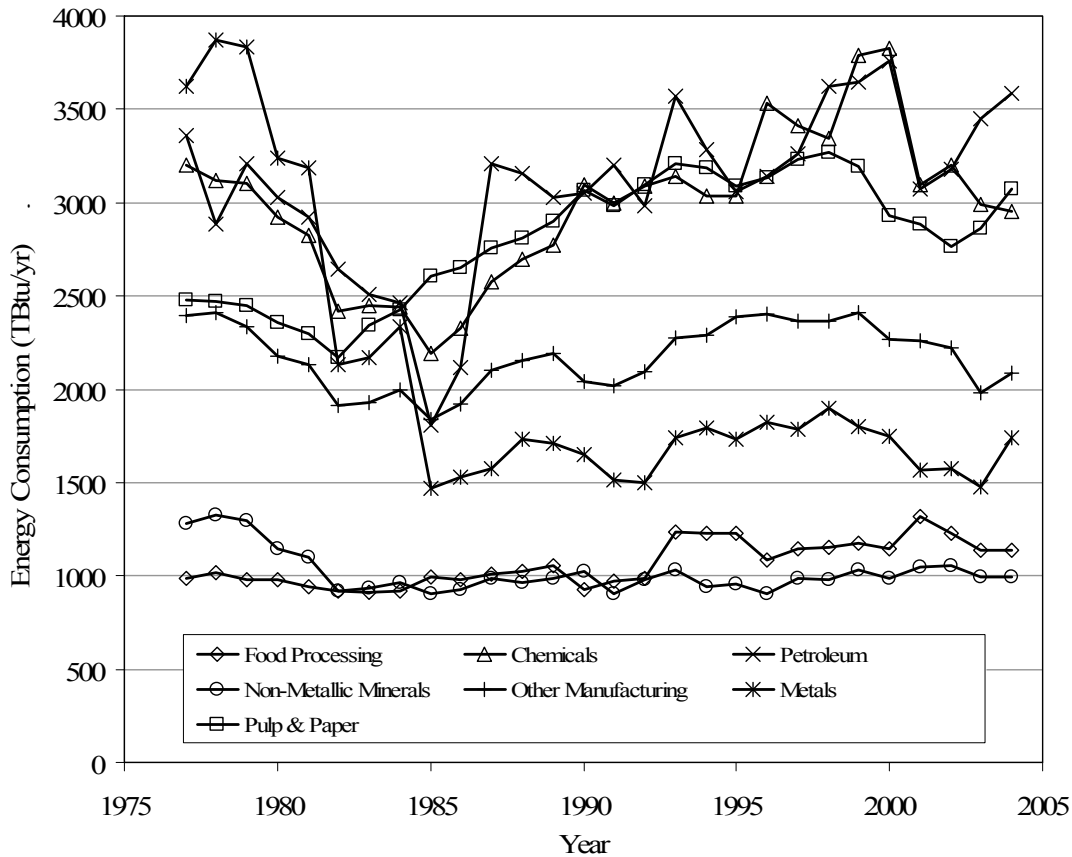
Industrial Delivered Energy

Figure 2. US Historical Annual Energy Consumption, by Industry (Source: 1974-1988 EIA, 1989-2004 PNNL)

2.1 US Industrial Energy Consumption by End-Use

However interesting they may be, aggregate statistics showing the sector as a whole are insufficient to model future trends in industrial energy consumption and the potential responses to climate policies. Fortunately, despite the heterogeneity of the industrial sector, most of the demand for energy across all of the industries is driven by the demand for a small set of key, common energy services such as process heat, steam, machine drive, and chemical feedstocks. In turn, the commonality of the energy services is helpful in that the set of energy technologies used in the industrial sector can be reduced to those needed to provide those services. From Figure 3, Pulp and Paper, Chemicals, and Food Processing are major consumers of steam (shown here as fuel input to boilers). Several industries, including Chemicals, Petroleum, and Metals also require significant amounts of process heat (dry heat rather than steam).
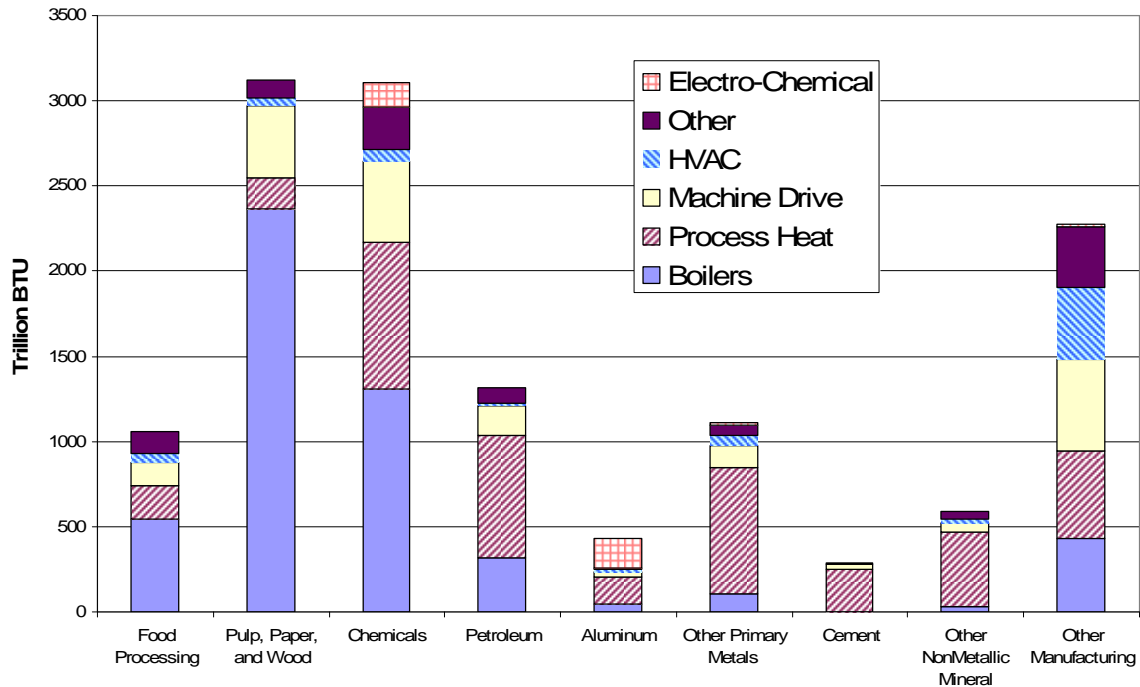
Figure 3. US 1998 Annual Energy Consumption, by Industry and Energy Service (aggregated by O^bjECTS MiniCAM Categories, discussed in next section. Source: 1998 MECS, EIA 1999)

Electricity provides most of the energy for the electro-chemical, machine drive, and HVAC services. Process heat has been mainly generated by natural gas, as a clean-burning fuel is required for this service. Electricity can also be used to generate process heat in some applications, but it is generally more expensive.

In contrast, steam can be generated by using a number of fuels, and the fuel mix for steam does vary across industry. As shown in Figure 4, currently, the Pulp and Paper Industry relies on biomass as it has access to inexpensive waste products. Across all industry groups, some coal and oil are also used, but natural gas dominates steam supply in most industrial sectors. Under a climate policy, emissions could be reduced by using commercial biomass to generate steam in more industries.
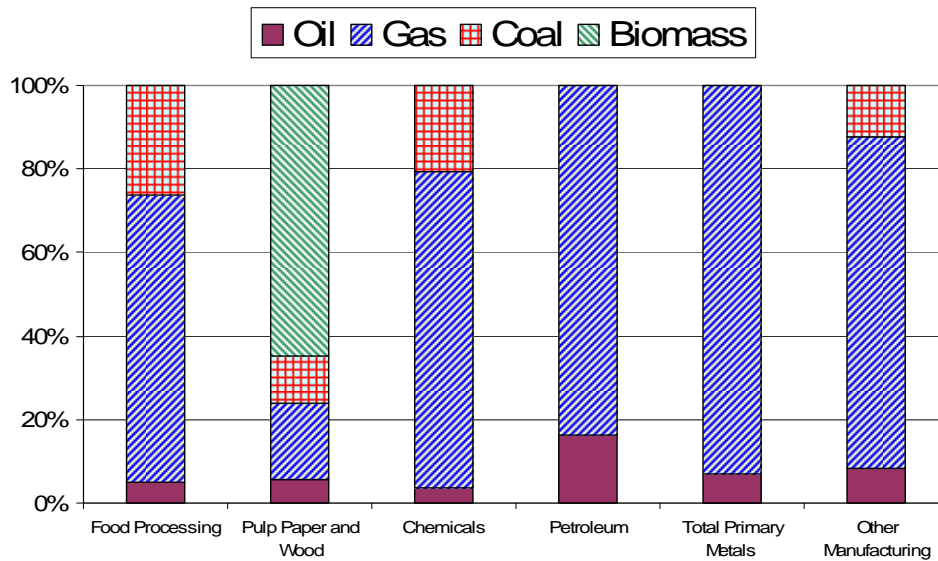
Figure 4. US Steam Production by Fuel and Industry in 1998 (Source: 1998 MECS, (EIA 1999), with grouping by the authors)

2.2 CO$_2$ Emissions and Potential Sources of Mitigation

Industrial sector CO$_2$ emissions are slightly lower than levels reached 30 years ago, as shown in Figure 5. This follows the pattern of energy use shown in Figure 1 above to some extent, but that figure also indicates a slight shift away from coal and oil to less carbon-intensive natural gas, as well as a slight trend toward electrification. Without an analysis of the fundamental drivers, it is difficult to determine if this flat trend of emissions is likely to persist. For example, EIA's recent Annual Energy Outlook (AEO) projects US industrial emissions to grow by nearly 30% from current levels by 2030 (EIA, 2006). As with total energy, the aggregate statistics are an important set of intelligence, but they are not sufficient in analyzing what future emissions may be and how those emissions could be mitigated.
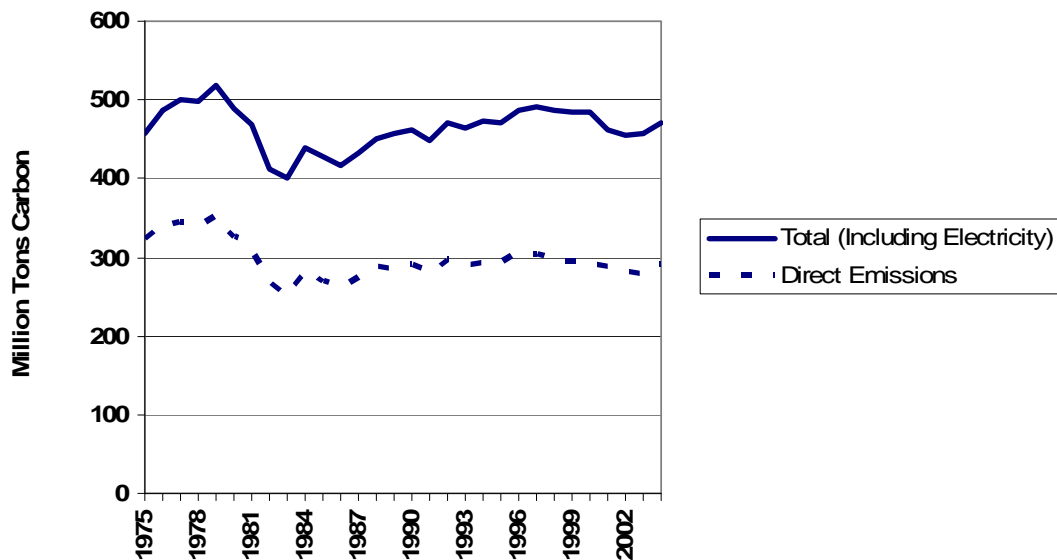
Figure 5. US Industrial Sector CO$_2$ Emissions (Source: EIA, 2005a)

Technological sources of emissions reductions could develop in several areas. The specific technologies that produce the basic industrial energy services such as heat and machine drive are already highly efficient. For example, current efficiencies to produce steam or heat from burning natural gas exceed 80%, while the efficiencies of electric motors exceed 90%. Consequently, although using increasing the efficiency of end-use energy technologies is an important goal, by itself it is relatively limited as a means of making major reductions in CO$_2$ emissions in many industrial sectors.

Because of the high energy efficiencies of the service technologies, future reductions in industrial energy intensity are more likely to come from re-designs and fundamental changes in the processes used to manufacture industrial products. An example of a process change would be a re-design of a manufacturing system or an advance in materials so that less heat is required to produce a product. The potential for process changes is more industry-specific than the more generic industrial energy services, although there are some promising new processes that could have wide application. Membranes, for example, can selectively separate one or more materials from a liquid or gas. This could potentially replace energy-intensive separation processes in a number of industrial sectors such as food processing, chemicals, paper, petroleum refining and metals industries. Another potential improvement is improved use of low-grade fuels produced as by-products by a number of industries. These fuels sometimes combusted in boilers to generate steam or heat. Gasification technologies could increase the efficiency of using low-grade fuels (Worrell *et al.*, 2004), although this technology might also have to complete for these with advanced biological conversion processes that could convert by-products to high grade liquid fuels such as ethanol. Note also that the enabling technologies for these and other process changes may not all arise out of traditional energy research but may also stem from advances in materials science or information technology.

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Another potential source of carbon emissions reductions is switching to fuels or energy sources with lower carbon content to make steam or heat. Industries such as pulp and paper, wood products, and food processing already use a substantial amount of renewable waste biomass as fuel. Industries without a ready source of waste biomass might use more commercial biomass, perhaps including gasification to produce process heat, as an alternative to natural gas. Increased electrification is possible in some services, but its economically viable use will be limited in services where large amounts of heat or steam are required. For some applications, the economic response may be to continue using fossil fuels even while paying an emission premium.

Cogeneration of electricity along with steam and heat (also called combined heat and power or CHP) is a technology that increases the net energy efficiency of the system. Electricity generated could be used on-site or sold to the grid. Cogeneration could reduce economy-wide emissions by reducing the use of fossil fuels that would be used elsewhere in generating electricity. Cogeneration would be best suited to large facilities with a steady demand for steam or heat. CHP has a clear energy efficiency advantage as compared to obtaining steam or heat on site while obtaining electricity from conventional central station power generation. CHP typically requires only about 75% of the primary energy that separate heat and power systems require (Kaarsberg and Roop, 1998).

In addition to emissions from burning of fossil fuels, some industries such as steel and cement also have a substantial amount of direct carbon emissions as a by-product of their materials processes. In an efficient carbon policy, potential mitigation of these emissions must also be considered, through means such as materials substitution or CO_2 capture.

A final note: unlike services in the buildings and transportation sectors, the products of the industrial sector can be shipped across the globe. As a consequence, heavy industry has been shifting its energy-intensive manufacturing from developed to rapidly developing regions of the world. A climate policy limited to developed nations could accelerate that trend, with implications for changing emissions profiles and policies. The international scope of climate policies becomes critical to controlling emissions from industrial sector. Otherwise emissions can be shifted rather than reduced. Such shifts are not considered in this work, where only the industrial sector in the US is modeled in detail.

3. The ObjECTS-MiniCAM Approach for Modeling the US Industrial Sector

Our specific objective in building a detailed industrial energy sector module for the ObjECTS model is to develop sufficient industry, end-use, and technological detail to examine both the potential long-term impact of technology and process improvement options for improving energy efficiency and intensity as well as the potential for lower-carbon fuels renewable fuels. In order to accomplish this, our level of aggregation must allow us to differentiate the following components:

- key industry groups that differ in terms of their mix of energy end-uses (or services) long-term growth, and consequent demand for energy,

- within each industry group, major energy end-uses (i.e., services or processes), with potential for process improvements where possible, as well as the potential for cogeneration of heat and power, and

- within each energy end- use, a set of explicit technology and fuel options that will compete, based on relative economics and engineering limits, to provide each of these energy services in each industry group.

What follows is a description of our approach and methodology for making the appropriate industry, energy end-use, and technology aggregations and distinctions. This paper represents our initial working version of this model. As we gain insights from further exercising this detailed industrial sector model, we will continue to modify this design as appropriate. Because the ObjECTS model has been designed with flexibility as one of its primary features, modifying the details, such as adding industrial sectors, is readily accomplished given the appropriate data.

3.1 Overview of ObjECTS-MiniCAM

Computer models have played an essential role in providing decision support in regard to climate change issues. PNNL's MiniCAM has been a useful tool in our ability for informing the national and international climate change debate for more than a quarter century (Edmonds and Smith, 2006). The MiniCAM has a recursive, partial equilibrium representation of the global economy with emphasis on the energy, technology, agriculture, and land-use and a 15-year time step to quickly assess long-term emissions of greenhouse gases. The MiniCAM as used here has 14 regions, one of which is the U.S., with markets in energy and agricultural products. The MiniCAM is well suited for addressing climate change questions with a long-term perspective (i.e., multi-decade to century-scale perspective). The model has been used extensively for the U.S. Department of Energy including analysis for the US Climate Change Technology Program (CCTP) (Clarke, Wise, *et al.*, 2006) and Climate Change Science Program (CCSP) (Clarke *et al.*, 2007); served as the primary analytical framework for PNNL's Global Energy Technology Strategy Project (GTSP) Capstone Report (Edmonds, *et al.* 2007); and also was one of the models employed to develop the IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic and Swart, 2000).

The equation structure of the MiniCAM is described in Edmonds *et al.* (2004). Its energy-economy roots can be traced back to Edmonds and Reilly (1985). The MiniCAM begins with a demographic profile for each region, derives the regional labor force, and combines this with assumptions about the long-term equilibrium rate of labor productivity to derive potential Gross Domestic Product (GDP). Realized GDP is the potential GDP modified by the feedback effect of energy costs. Realized GDP sets the system scale. Energy, agriculture, land and emissions-rights markets are solved endogenously within this aggregate economic frame. The model provides an internally consistent, equilibrium analysis of technologies within the global system. General equilibrium effects and connections, however, are not modeled. That is, the allocation of capital and labor across production processes are assumed to occur within the context of larger long-term economic equilibrium. While this simplification could exert a downward bias on the estimate of economic costs of emissions mitigation, in practice the effect seems small (see for example, Weyant, 2004) for the time scales considered here.

Until recently, as with most long-term models, the MiniCAM has maintained a strong focus on energy production, transformation and use. The model tracks the production of fossil fuels, namely oil, natural gas, and coal as well as non-fossil primary energy forms including nuclear, wind, solar, and hydro. The model transforms primary energy forms to those that are consumed in final use. Transformation processes include, refining, power generation, and hydrogen production. A variety of technology options are available to produce all of the end-use energy forms: liquids, gases, coal, biomass, electricity and hydrogen. The model has been continuously revised and updated to include an expanded set of processes, such as agricultural production and land-use allocation, and additional technology options.

MiniCAM has included a fully-integrated model of regional agriculture and land-use for over a decade (Gillingham, Smith, *et al.,* 2007). This "ag/land-use" model considers all demands and uses for lands: including food crops, pasture, forests, and unmanaged lands. The production of biomass energy crops is a crucial link between the ag/land-use model and the MiniCAM energy markets. The MiniCAM model does not simply assume that biomass can be supplied at a given price. Instead, land used to grow commercial biomass crops must compete economically with these other demands for land. A large-scale expansion of commercial biomass crops can not be done without considering the impacts of that demand for land on the food and other agricultural requirements of future populations. This internally-consistent consideration of biomass energy crops turns out to be an important factor of the industrial sector analysis here that could not be done without the context of an integrated model.

The industrial sector module described in this paper was developed within the O[bj]ECTS framework (Kim *et al.,* 2006). The Object-Oriented Energy, Climate, and Technology Systems (O[bj]ECTS) framework is a flexible modeling system written in the C++ language using eXtensible Markup Language (XML) input and output formats. The same general equation structure as used in previous MiniCAM model versions was implemented within the O[bj]ECTS framework. The virtue of the O[bj]ECTS-MiniCAM approach is that the each component model, such as the industrial sector model detailed in this paper, is integrated, internally consistent and theoretically compatible with the larger MiniCAM framework.

3.2 Selection of Energy End-Use Categories and Industry Groups

Our first step was to determine an aggregation of categories of energy end-uses and industries that would be useful and practical for this application. For the manufacturing sector, Manufacturing Energy Consumption Survey (MECS), maintained by the EIA, proved invaluable and was our primary source. At the time we began this model development, the 1998 MECS (EIA, released in 1999) was the most recent complete version of the manufacturing sector, and it is the basis for our initial calibration data used in this report (since then, MECS 2002 has been completed by EIA, and we will consider using it for future updates of our work.). For non-manufacturing sectors, we use the estimated fuel consumption for agriculture, mining, and construction from the Annual Energy Outlook supplement tables from the (EIA, 2006b).

Table 1 shows the total fuel consumption by energy end-use across all industries represented in the 1998 MECS[2]. The relative magnitudes of energy consumption by end use along with the

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[2] Adapted from Table E6.4. End Uses of Fuel Consumption, 1998 (URL: ftp://ftp.eia.doe.gov/pub/consumption/industry/d98e6_2.xls). Table 6.4 is used rather than Table 6.2 as 6.4 expresses

relative fuel shares within end-uses provide a useful guide for selecting end use categories for modeling. From the MECS data in Table 1, we see that the major end-uses of energy are boilers, process heat, machine drive, and facility heating, ventilation and air conditioning.

Table 1. Total Fuel Consumption by End-Use for all MECS Industries, 1998, trillion BTU

	Electricity	Liquid Fuels	Natural Gas	Coal (excluding Coal Coke and Breeze)	Total
Boiler Fuel	29	308	2,538	770	3,645
Process Heating	363	185	3,187	331	4,066
Process Cooling and Refrigeration	209	2	22		233
Machine Drive	1,881	25	99	7	2,012
Electro-Chemical Processes	354				354
Other Process Use	13	5	52		70
Facility HVAC	289	14	403	4	710
Facility Lighting	227				227
Other Facility Support	53	7	40		100
Onsite Transportation	5	59	5		69
Conventional Electricity Generation		6	210	27	243
Other Nonprocess Use	4	1			5
End Use Not Reported	71	12	72	3	158
Total Fuel Consumption	**3,498**	**625**	**6,644**	**1,143**	**11,910**

The other important end-use grouping characteristic for our modeling is the relative fuel mix, both in the data and in the future potential. Boilers use a broader mix of fuels than process heating, which is mostly natural gas with some electricity. Machine drive and electrochemical process are dominated by electricity. HVAC and the rest of the end-use categories use a mix of gas, oil, and electricity.

electricity as "Net Demand for Electricity", which includes Industrial Sector consumption of electricity generated on-site. This is the relevant metric for us as we do model cogeneration of electricity.

Based on these factors we have aggregated the MECS end-uses into six categories: steam (boilers), process heat, machine drive, electro-chemical processes, HVAC, and other. These categories explicitly cover the majority of industrial energy use, with the "Other" category comprising the remaining 8% in 1998. Table 2 shows the mapping of MECS end-uses to our set of O^{bj}ECTS model industrial energy end-use categories.

Table 2. Mapping of MECS to O^{bj}ECTS end-use categories

MECS End-Use	O^{bj}ECTS End-Use Category
Boiler Fuel	Boilers
Process Heating	Process Heat
Process Cooling and Refrigeration	Other
Machine Drive	Machine Drive
Electro-Chemical Processes	Electro-Chemical
Other Process Use	Other
Facility HVAC	HVAC
Facility Lighting	Other
Other Facility Support	Other
Onsite Transportation	Other
Conventional Electricity Generation	Other
Other Non-process Use	Other
End Use Not Reported	Other

Our selection of industrial groups is determined by grouping industries together by their patterns of energy use in terms of energy end-uses, and the availability of appropriate activity level drivers within our modeling framework. Table 3 shows the mapping between the NAICS (North American Industrial Classification System) codes for each industry to O^{bj}ECTS model industrial groups for manufacturing industries.

Table 3. Mapping of MECS NAICS Industry Codes to O^{bj}ECTS Industry Groups

NAICS Code	Industry Name	O^{bj}ECTS Industry Group
311	Food	Food Processing
312	Beverage and Tobacco Products	Food Processing
313	Textile Mills	Other Manufacturing
314	Textile Product Mills	Other Manufacturing
315	Apparel	Other Manufacturing
316	Leather and Allied Products	Other Manufacturing
321	Wood Products	Pulp, Paper and Wood
322	Paper	Pulp, Paper and Wood
323	Printing and Related Support	Other Manufacturing
324	Petroleum and Coal Products	Petroleum
325	Chemicals	Chemicals
326	Plastics and Rubber Products	Other Manufacturing
327310	Cement	Cement
327	Nonmetallic Mineral Products (net of Cement)	Other Non-Metallic
3313	Alumina and Aluminum	Aluminum
331	Primary Metals (net of Aluminum)	Other Primary Metals
332	Fabricated Metal Products	Other Manufacturing
333	Machinery	Other Manufacturing
334	Computer and Electronic Products	Other Manufacturing
335	Elec. Equip., Appliances, Components	Other Manufacturing
336	Transportation Equipment	Other Manufacturing
337	Furniture and Related Products	Other Manufacturing
339	Miscellaneous	Other Manufacturing

We model the cement industry separately because its non-combustion emissions of CO_2 justify special attention. An additional nonmetallic minerals category includes the production of lime and other processes that also produce non-combustion direct carbon emissions. Aluminum smelting is treated separately from other metals due to the large amount of electricity used in this process. Aluminum merits consideration also because it may have an increased importance in the future under climate policies. The pulp and paper industry is separated due to its high use of biomass fuels.

Table 4 shows final energy consumption by end-use for our manufacturing industrial categories, not including feedstock energy use.[3] From this table the large amount of energy consumption in the chemicals industry is apparent, as is the magnitude of energy consumption for boilers and process heat across several industries. The other manufacturing category comprises about a fifth of industrial energy consumption across a wide range of end-uses. Feedstock use of fossil fuels for is addressed in a later section.

Table 4. Final Energy Consumption, excluding feedstocks, from 1998 MECS: OᵇᴶECTS Industry Groups by End-Use Categories, trillion BTU

	Boilers	Process Heat	Machine Drive	HVAC	Other	Electro-Chemical	Total	*Percent of Total Manufacturing*
Food Processing	547	191	140	53	130	0	1,061	*8%*
Pulp, Paper, and Wood	2,368	177	424	46	108	2	3,125	*23%*
Chemicals	1,308	864	471	72	252	141	3,108	*23%*
Petroleum	314	721	173	15	92	0	1,315	*10%*
Aluminum	42	161	33	10	10	178	434	*3%*
Other Primary Metals	104	739	134	59	57	15	1,108	*8%*
Cement	1	246	35	1	4	0	287	*2%*
Other Non-metallic Minerals	27	444	52	23	40	1	587	*4%*
Other Manufacturing	428	520	532	426	354	16	2,276	*17%*
Total	5,139	4063	1,994	705	1,047	353	13,309	

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[3] The totals in this table are computed from 1998 MECS Table N6.4 supplemented with biomass byproducts used in the Pulp, Paper, and Wood industry, as stated in 1998 MECS Table 5.2.

The relative composition of energy end-uses by these industry groups is shown graphically in Figure 6. From this data, Food Processing, Pulp and Paper, and Chemicals Industries require a large fraction of boiler energy, while Pulp and Paper demands relatively more machine drive than the others. The Cement, Petroleum and the Other Primary Metals industries both require large quantities of process heat, while Aluminum differs in its significant demand for electro-chemical processes. The Other Manufacturing industry group demands a wide range of energy services.
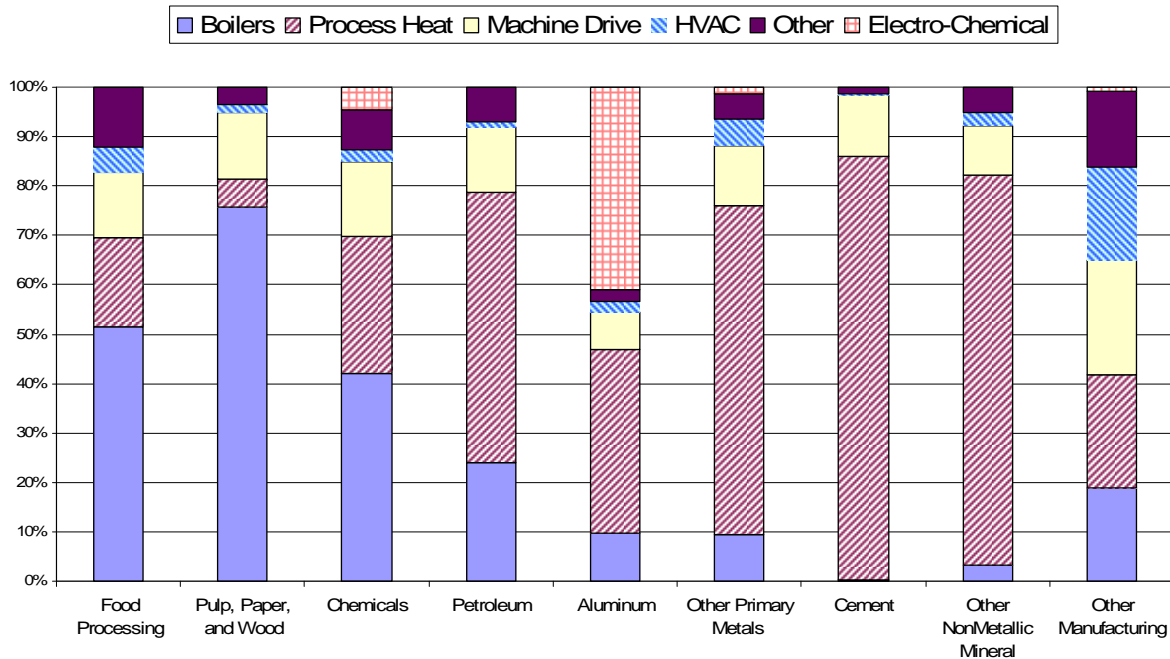

Figure 6. Fraction of US 1998 Industry Energy Consumption by End-Use, excluding feedstocks. Source: 1998 MECS (EIA 1999)

The end-use demands for each industry group is a critical factor in determining mitigation options. For example, the Pulp, Paper, Wood and the Chemicals industries are similar in that they both have a large demand for boilers, and consequently cogeneration potential. The boiler and cogeneration technology options used in paper differs from that in chemicals. The pulp and paper industry has large amounts of inexpensive wood and byproducts available so a large fraction of the electricity used is cogenerated using steam turbines supplied by bed boilers. In contrast, the chemical industry, as a large user of natural gas as feedstock and for process heating, would rely on producing cogenerated electricity from the use of combined-cycle turbine systems, which can burn both natural gas and byproduct gases. Thus, these two industries need to be treated separately so that we can take into account different technology and fuel options.

Finally, we also need to include non-manufacturing industry groups, which, by definition, are not part of the MECS data. For non-manufacturing industries, we employed the grouping used by EIA in the Annual Energy Outlook (EIA, 2006), as that also proved to be the most practical source of aggregated data. Specifically, we model Agriculture, Construction, and Mining.

Because these groups are highly aggregate and heterogeneous, we have modeled one generic energy end-use per each of these industry groups. Fuels used to provide this end-use are calibrated based on AEO projections for 2005, and are allowed to compete based on costs in future modeled years. In addition, there is a separate feedstock end-use for Construction to account for asphalt demand. Table 5 shows fuel totals for these three non-manufacturing industry groups as projected in the AEO for 2005.

Table 5. Non-Manufacturing Industrial Groups Energy Consumption, trillion BTU, as projected in the AEO for 2005

	Oil	Gas	Coal	Renewables	Electricity	Feedstocks	Total
Agriculture	742	218	0	23	172		1155
Construction	360	277	0	0	115	1237	1989
Mining	383	1948	32	2	230.8		2596

3.3 Modeling of Energy End-uses, Technologies, and Fuel Options

The ObjECTS framework is designed so that within each energy end-use, production, and transformation (e.g., electricity, hydrogen, synfuels) sector multiple technology options compete based on their relative economics. Technologies and their fuels compete and penetrate the market on the basis of costs –fuel, capital and O&M costs. The competition among alternative technologies and fuels is based on a logit choice formalism. A logit equation determines market shares based on the relative costs of producing an output, including capital and energy costs, assuming a distribution of costs (Clarke and Edmonds, 1993). This differs from a pure optimization approach where the least cost option can gain the entire market unless it is otherwise constrained.

This economic competition allows the examination of the impact of fuel price changes on technology choice. For example, coal, oil, natural gas, and renewable fuels can be used in operating boilers to generate steam. Under a carbon policy, the cost of using coal increases, and industries will switch to less carbon-intensive fuels such as natural gas or whatever renewable fuels are available to that industry. The carbon policy might also encourage increases in the use of cogeneration. Note that there is no intrinsic limit on the number of technologies that can be incorporated into the ObjECTS model for each end-use.

Figure 7 provides a simple schematic showing the competing technologies for providing steam in the Chemicals industry. From this figure, we see how multiple energy end-use demands are required to produce output in the Chemicals industry, and that multiple fuel and technology options are available to provide each. This figure also shows how CHP (cogeneration) technologies will compete with steam-only boilers to provide the boilers (or steam) end-use. While CHP technologies will typically have a higher cost, they produce dual products: steam and electricity, and their higher cost can be offset by the value of the electricity produced. The overall mix of boiler and CHP technologies and fuels will be determined by the relative economics at each time period.
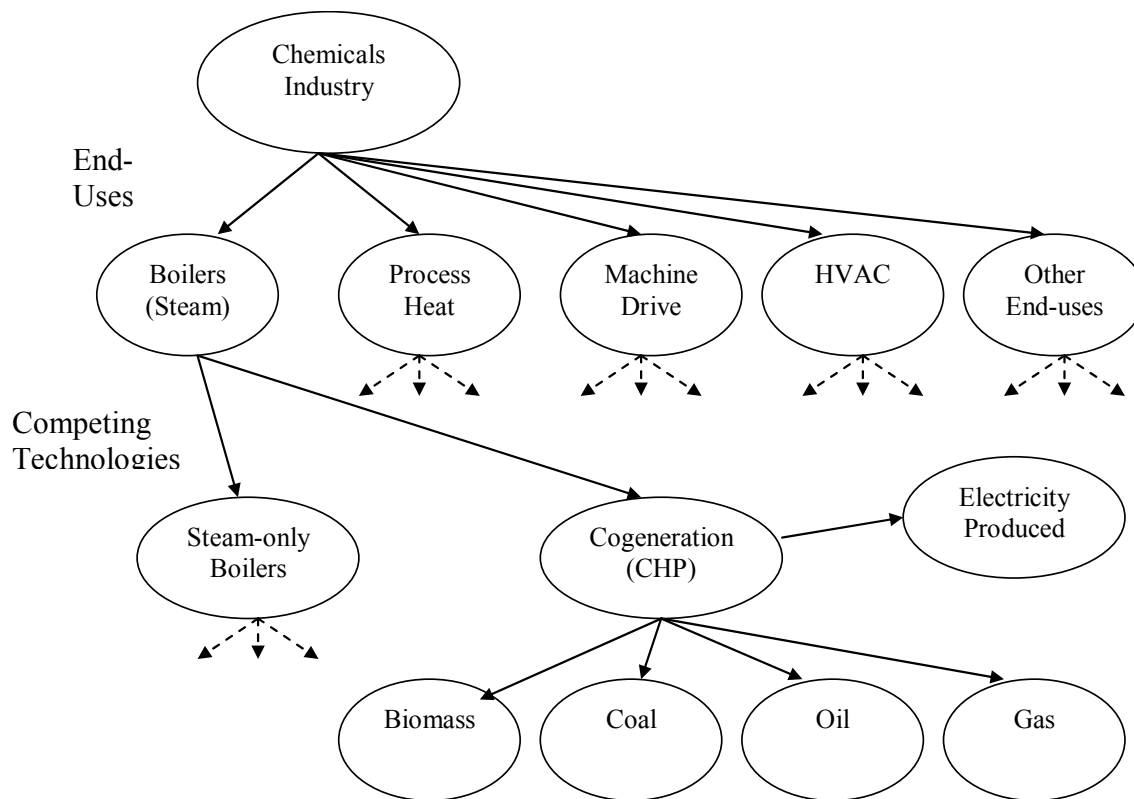
Figure 7. Simplified Schematic of ObjECTS End-Use and Technology Structure for the Chemicals Industry

The model was calibrated for model years 1990 and 2005 with energy consumption data from MECS 1991 and 1998, respectively. This calibration data, plus technology efficiency information, determines the process energy service coefficients for each industrial sector. For 2005 we have used the MECS industrial sector data details on energy end-use and fuel mixes from 1998 and scaled up the totals to 2005 estimates using the 2006 Annual Energy Outlook (EIA, 2006), while 1991 MECS values were scaled down to our model year 1990 in the same manner. As we have discussed, MECS 2002 was still being updated at the time we were constructing this model, and we may update to newer MECS data for future analyses.

Average efficiencies for generating steam in new boilers using coal, oil, gas, and biomass were taken from data compiled by the Council of Industrial Boiler Owners (2003). Efficiencies for electric motors were taken from NEMS (EIA, 2005b). Given the already high efficiencies in these end-uses a nominal efficiency improvement of 0.1% per year was applied to all end use technologies. Efficiency data for other industrial energy service sectors is not available and was set to an arbitrary index value. Efficiency data for cogeneration technologies were adapted from The Institute for Thermal Turbomachinery and Machine Dynamics (2002) for steam, gas turbine, and gas combined cycle technologies. In our modeling of cogeneration in ObjECTS, the investment in cogeneration is based on relative economics as compared with stand-alone boiler and process heat systems. The cogeneration system would have a higher capital cost and use more fuel than a stand alone boiler or burner, but it would be compensated for the electricity it would produce, and decrease the amount of electricity that would have to be produced elsewhere

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in the system. The 2005 calibration value for cogenerated electricity was taken from the 1998 MECS.

3.4 Modeling Industrial Processes

Industrial processes are represented as Leontief production functions. Within each industrial grouping, the production processes is modeled as a set of energy-end service demands required to produce a unit of output. For example, to produce a unit of output from the Chemicals industry, requires x units of steam, y units of process heat, and z units of other. The input-output coefficients required to drive these production functions are determined by the MECS data. The service output for each end-use demand is the energy consumed divided by the end-use efficiency for the processes considered. These coefficients were assumed constant over time for the results shown here, although they can be varied to represent process changes. Note that, even with the energy service coefficients are fixed, the fuels used to produce the energy services can change over time. While we can not replicate the degree of process flow detail found in more focused industrial sector models, this structure can represent the basic dynamics and even structural changes over time. The impact of process improvements can be modeled by decreasing the proportion of specific end-uses as appropriate.
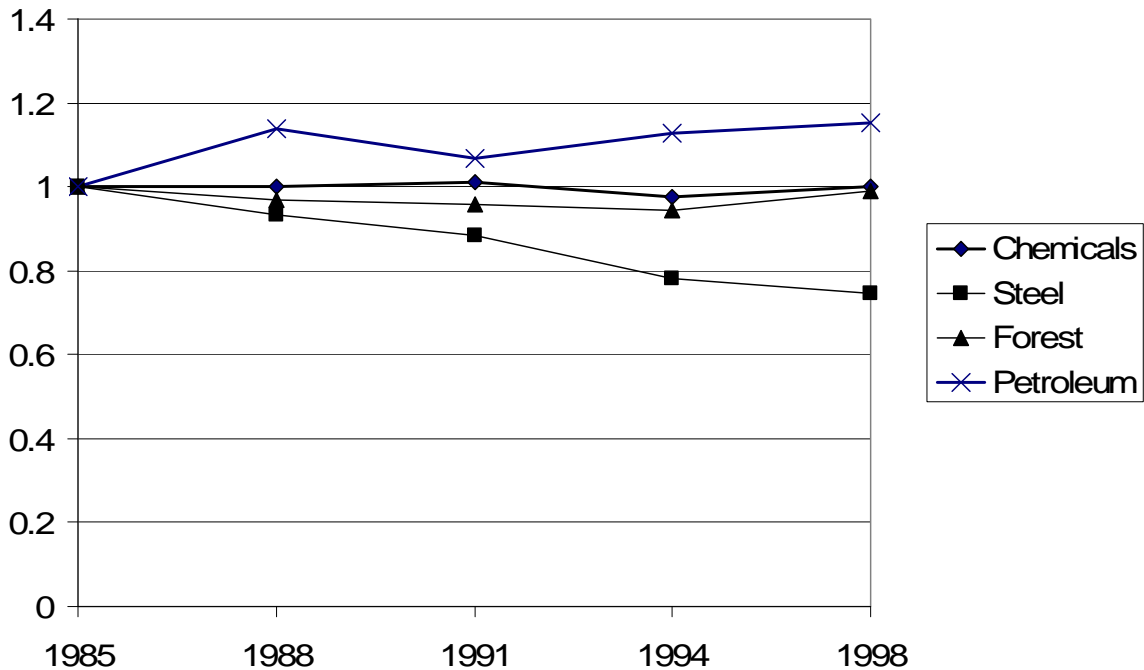

Figure 8. Index of Energy Demand relative to Physical Output. Source: 1998 MECS EIA 1999)

As a proxy for aggregate process and efficiency changes over the last 20 years, Figure 8 shows the ratio of energy consumption to physical output, indexed to 1985, for select industries. Given the aggregate nature of these industrial categories, measures of total physical output are imperfect, and virtually meaningless for some industry groups. This measure indicates significant process change in the steel industry (e.g., an increase in the use of electric arc

furnaces and recycled steel) which has lowered aggregate energy intensity. In the other industries shown, the trends are flat indicating that little large-scale process improvement has occurred over the time period shown.

3.5 Modeling Consumption of Energy Feedstocks

Approximately one quarter of the energy used in the industrial sector is in the form of energy feedstocks, i.e. nonfuel uses of energy sources. Distinguishing feedstocks from fuel consumed as energy is critical because much of the total fossil fuel consumed as feedstocks can be assumed to be non-emitting in terms of CO_2. Instead, some portion of these feedstocks is used in a way that sequesters the carbon content for a significant time. Natural gas, petroleum, asphalt and coking coal are some examples of fossil fuels which are consumed for non-energy uses. Some of these uses include application as solvents, lubricants, waxes or as raw materials in the manufacture of plastics, rubber and synthetic fibers. Emissions may arise from non-energy uses during manufacture of a product or during the product's lifetime (e.g. solvent use). It is estimated that about 65% of the total carbon content of fuel used in feedstocks is sequestered (Inventory of U.S. Greenhouse Gas Emissions and Sinks: EPA, 1990-2003, 2005). This proportion has remained approximately constant since 1990.

Table 6 shows the feedstock use of fossil fuels by industry group for the year 1998. Petroleum, chemicals and primary metals consume the largest portion of energy used by industries as feedstocks (99%). We therefore add an additional end-use feedstock category for these three industries.

Table 6. Feedstock Consumption by Industry, 1998 MECS, trillion BTU

	Total	% of Total Feedstock Use
Petroleum and Coal Products	3,748	51
Chemicals	2,772	38
Primary Metals	758	10
Other Industry	62	1
Total	**7,340**	

Table 7 summarizes this feedstock fuel detail, showing the percentage of each industry's total feedstock consumption by each feedstock fuel. For example, liquid fuels comprise 65.1 percent of the fuels used as feedstocks in the chemical industry. The chemicals industry uses primarily LPG and NGL while primary metals largely uses coal. The MECS data categorizes some feedstock use in an "other"[4] category regardless of fuel type. For modeling purposes, we have assumed the other fuel category is petroleum-based.

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[4]'Other' includes energy that respondents indicated was used as feedstock/raw material inputs. For the petroleum refining industry only (NAICS 324110), the feedstocks and raw material inputs for the production of nonenergy products (i.e., asphalt, waxes, lubricants, and solvents) and feedstock consumption at adjoining petrochemical plants are included in the 'Other' column, regardless of type of energy. Those inputs and feedstocks that were converted to other energy products (e.g., crude oil converted to residual and distillate fuel oils) are excluded (Footnote, Table d982.2,: Nonfuel (Feedstock) Use of Combustible Energy, 1998 MECS data).

Table 7. Percentage of Each Industry's Total Feedstock Consumed, by Fuel

	Liquids	Natural Gas	Coal	Other
Petroleum and Coal Products	0.0	0.0	0.3	99.5
Chemicals	65.1	26.2	0.8	8.0
Primary Metals	0.0	5.8	86.8	7.1
Other	3.6	7.1	1.8	64.3
Total All Industry	**24.7**	**10.7**	**9.5**	**55.1**

4. A Scenario of Future US Industrial Energy Consumption and Response to a CO_2 Emissions Policy

As an integrated assessment model, one if the primary uses of O^{bj}ECTS MiniCAM is to explore the impact of climate policies on energy consumption, land-use, and the resulting greenhouse gas emissions in the context of economic growth, energy resources, and technological advances over a century-long time horizon. This kind of analysis also provides insights into technological challenges and opportunities for reducing future emissions.

In this section, we explore the potential impacts of a climate policy on energy consumption in the US industrial sector. This exercise first requires constructing an underlying scenario of industrial energy consumption and emissions without a CO_2 policy. Then a climate policy scenario is modeled in which CO_2 emissions are constrained to follow a path resulting in stabilization of atmospheric concentrations at 550 ppmv, as will be described.

The model results include fuel consumption for each of the industry groups, end-uses, fuels, and technologies in each time period. We present below aggregate results for energy consumption and carbon emissions under reference and climate policy cases. In addition, we will focus on the key technology of cogeneration as an illustration of the interactions that occur through embedding an industrial model within an integrated framework.

4.1 Industrial Energy Scenario Drivers

The purpose of constructing a long-term scenario in an integrated assessment model is not to attempt to predict the future. Rather, the goal is to provide a transparent background for analysis and discussion. Although the absolute magnitude of future energy demands and the nature of industrial activities can not be known with certainty, modeling and analysis such as that presented here can produce meaningful insights into the technological and economic choices that may affect energy consumption and how these choices may be affected by a climate policy.

In addition to the energy and technology assumptions discussed above, one of the main drivers of energy consumption in all sectors is the population and economic growth assumptions. This scenario assumes moderate population growth and robust economic growth (Figure 9). By 2095 total U.S. population is assumed to increase by about 50% over today's level while total U.S. GDP per capita nearly triples. In contrast to other high income regions like Europe and Japan,

which see little population growth, US population growth fueled in large part by immigration. Note again that although our paper is focused on the US, assumptions for the rest of the world are also important influences of what happens in the US energy system.
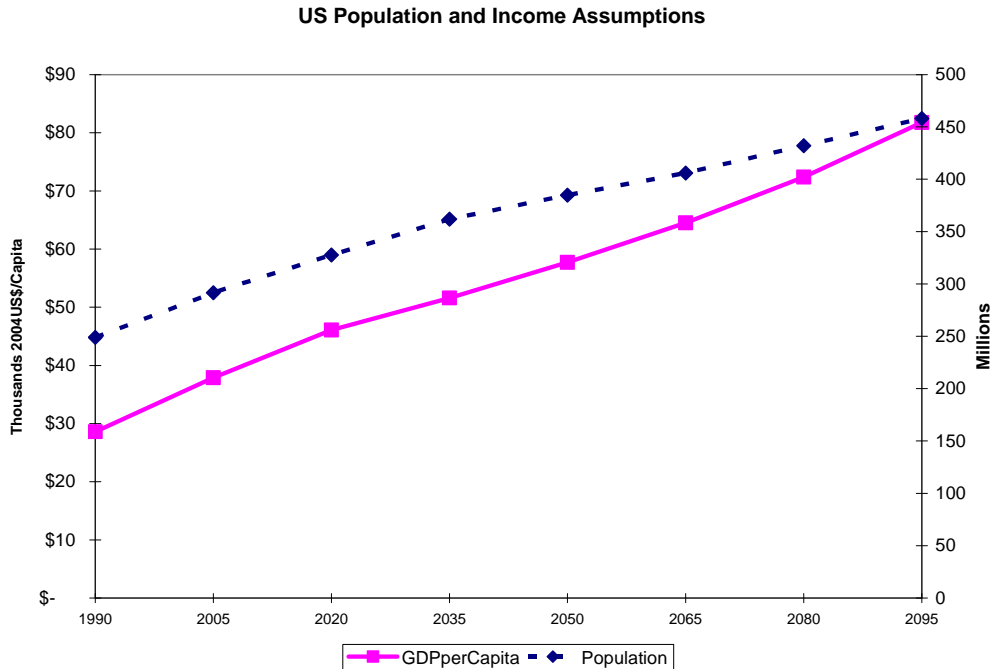
US Population and Income Assumptions

Figure 9. Demographic and Economic Assumptions for the US

Differential growth in activity by industry will be a key determinant of future energy consumption and emissions. To model this, we developed econometric estimates of the historical relationship between energy consumption and US GDP and population. We use one of two forms for the demand function. For some activities energy demand is best modeled as a function of national GDP. For other activities, where energy services have begun to saturate, it may be more appropriate to model energy as proportional to population, with a secondary dependence on per capita-income. For example, it is reasonable to assume that individuals (on an average) in the US would not consume substantially more food as incomes increase. Thus using population as a primary driver might prove to be a more accurate than national income. While the difference in these two approaches would be small in the near-term, the long-term effect could be significant if the relative rates of population and income growth change over time.

Defining our econometric estimates, the elasticity of energy with respect to income is defined as follows.

$$\eta = \delta ln(energy)/ \delta ln(income)$$

Thus the coefficient of a regression of natural log of energy on the natural log of income will provide an estimate of elasticity. With two alternative demand functions, we perform two regressions:

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GDP-based: *ln(industry energy consumption)* is regressed on *ln(real GDP)*

per-capita GDP-based: *ln(per capita industry energy consumption)* is regressed on ln(*per capita real GDP*)

We have estimated income elasticities for our US industrial groups using an ordinary least squares regression using time series of historical energy consumption data from 1977 to 2004 (Industrial Indicators worksheet, DOE, 2006) versus annual GDP and population (Economic Report of the President, 2006). Energy demand in the food processing and pulp and paper sectors was nearly proportional to population, so for these sectors the population based formulation was used for demand. The total GDP formulation was used for other sectors. In sectors where energy demand sharply decreased in the early part of the time series, presumably due to the oil price shock in that time period, the regression was conducted for data past 1985 in order to better match recent trends.

We present the resulting elasticity values for each industry group in Table 8 (rounded to the nearest 0.05, recognizing that it is not possible to be overly precise over the time period considered). Energy consumption in all industries grows with either income or population, although at different rates. Energy consumption in the petroleum and chemicals industries have been growing fastest, about half as fast as GDP. The remaining industries are growing at slower rates, with income elasticities of 0.1–0.2. The data for the non-manufacturing industry groups was not collected directly, so we have, somewhat arbitrarily, set the elasticity for this sector to 0.1 to match the elasticity for the Other Manufacturing category. Better data on each non-manufacturing industry over time is needed to determine the trends for these activities.

Table 8. Income Elasticities Derived for O^bjECTS MiniCAM Industry Groups

Industry Group	Driver	Regression Period	Income Elasticity (to nearest 0.05)
Food Processing	Population and PerCapita Income	1977–2004	0.00
Pulp Paper and Wood	Population and PerCapita Income	1977–2004	0.05
Chemicals	Total Regional Income (GDP)	1985–2004	0.55
Petroleum	Total Regional Income (GDP)	1985–2004	0.65
Aluminum	Total Regional Income (GDP)	1985–2004	0.15
Total Primary Metals	Total Regional Income (GDP)	1985–2004	0.15
Cement	Total Regional Income (GDP)	1977–2004	0.15
Other NonMetallic Mineral	Total Regional Income (GDP)	1985–2004	0.15
Other Manufacturing	Total Regional Income (GDP)	1977–2004	0.10
Agriculture	Total Regional Income (GDP)	NA	0.10
Mining	Total Regional Income (GDP)	NA	0.10
Construction	Total Regional Income (GDP)	NA	0.10

In constructing a scenario, these elasticity parameters are coupled with the population and economic growth drivers to model future demand levels for energy end-use services in these industry groups. Figure 10 shows the demand growth by industry in terms of energy service demands. These energy service demands differ from energy demands in that they are normalized at base year levels of assumed energy and process efficiency. Therefore, they should be considered as dimensionless indicators of the relative change in energy service demand across industries over time. Energy demand will not necessarily be proportional to energy service demand as the technologies that provide energy services, and the processes used to produce goods, could become more efficient.

Using the elasticities derived earlier, we find that the Chemicals and Petroleum industries exhibit strong growth in their demands for energy services (Figure 10), Pulp Paper and Wood and Food Processing industries show moderate growth, while the non-manufacturing and other industry groups exhibit relatively slow demand growth over time.
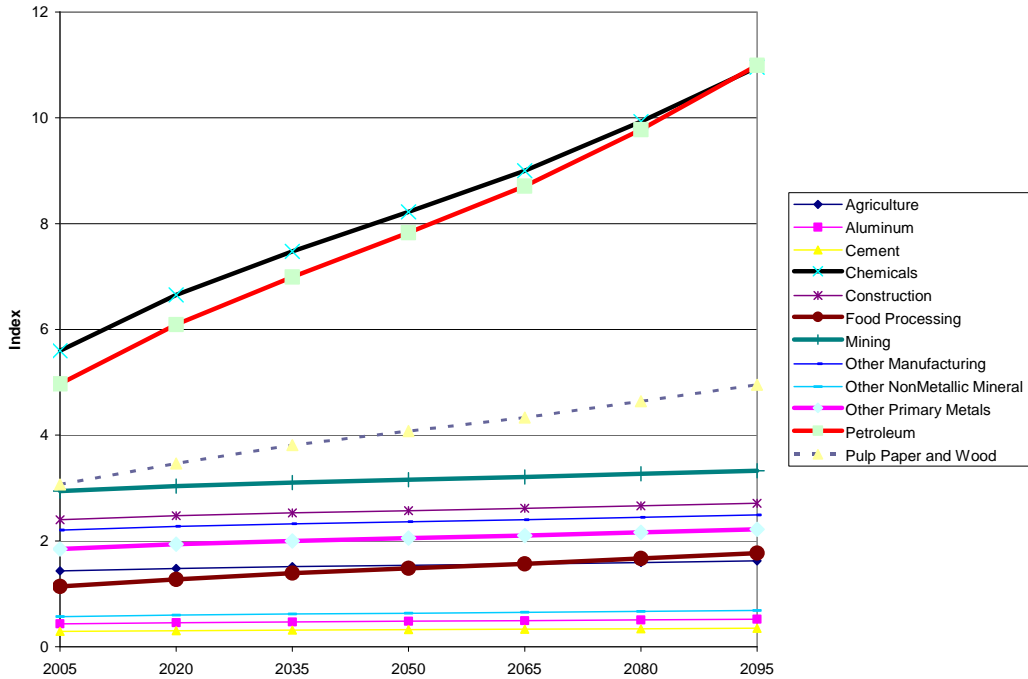
Figure 10. Energy Service Demand Growth

4.2 A CO$_2$ Emissions Reduction Policy

In the O^{bj}ECTS MiniCAM, the effect of a policy to reduce greenhouse gas emissions is felt by a value that is placed on carbon, which makes its way through the energy system, causing price-induced reductions in energy use, fuel switching and changes in technology adoption. The scenario described above was run for both a reference case, where carbon emissions are not constrained, and a policy case where global carbon dioxide emissions are constrained to follow a 550 ppmv stabilization path updated from Wigley, Richels, and Edmonds (1996). In the carbon policy case, the model adds a price to carbon emitting technologies proportional to their emissions, with the price adjusted each period until the emissions target is achieved. The carbon price per unit energy is (highest for coal, medium lower for oil, and lowest for gas, although even for natural gas consumption carbon prices can still be a significant factor in determining fuel and technology choice.

Figure 11 shows both the WRE 550 global emissions constraint path and the carbon price path that results in the MiniCAM model when this constraint is applied against this scenario. The technology scenario used here did not include the adoption of potentially transformative technologies such as geologic carbon dioxide capture and widespread adoption of hydrogen in the transportation sectors. The inclusion of these technologies would lower carbon prices. While this would likely change the magnitude of the response within the industrial sector this would not change the overall dynamics, which is the result of primary interest here. Note that this is just one possible policy scenario.
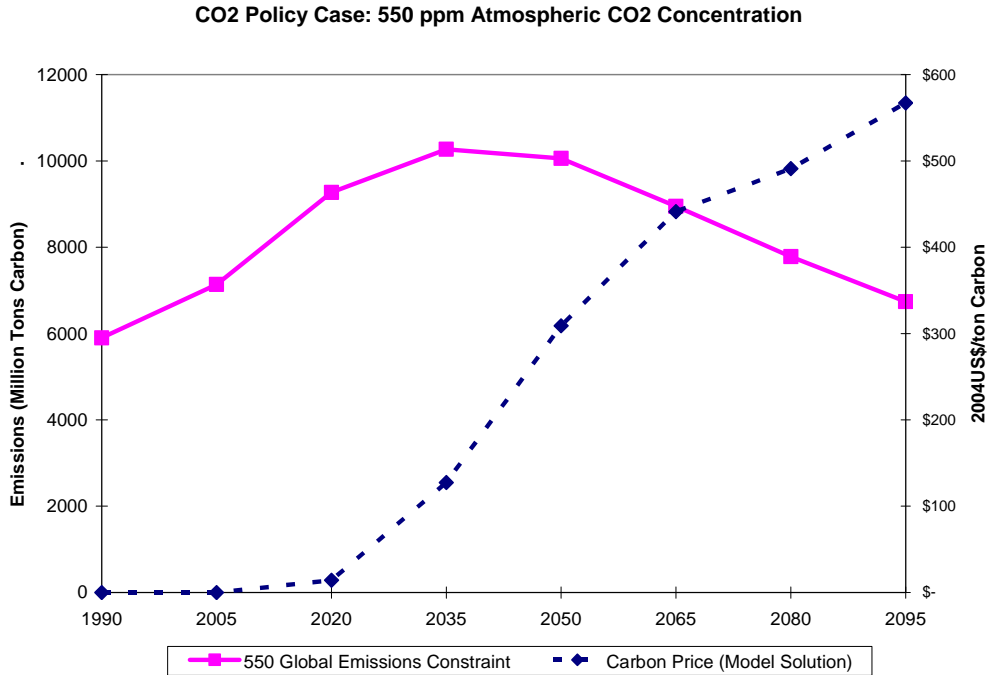
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CO2 Policy Case: 550 ppm Atmospheric CO2 Concentration

Figure 11. WRE 550 Global CO$_2$ Emissions Constraint

This CO$_2$ emissions constraint is applied globally across all regions and economic sectors. It is an economically efficient policy so that all users of fossil fuels see the same carbon price. The model solves for the carbon price that meets that global constraint, although any given carbon price path is just one potential scenario that depends on the economic and technology assumptions applied in all regions of the world. The US Industrial sector responds to the carbon price by adapting technologies with less carbon-intensive fuels to reduce emissions where it is economic to do so.

Figure 12 compares the US industrial sector CO$_2$ emissions with and without the CO$_2$ policy. Two sets of lines are shown. The first, labeled *total emissions*, is a more complete measure of industrial sector emissions that accounts for the indirect emissions associated with generating the electricity and refining the fuels purchased by the industrial sector. The second set is the *direct emissions*: those that occur at the point of fuel use inside the industrial sector.

Without a climate policy, emissions grow at a steady rate with total CO$_2$ emissions growing to about 700 million tons of carbon by 2095. Much of the growth in later years is driven by increases in indirect emissions as the growth in direct emissions is leveling off. Total industrial emissions grow more slowly than total US emissions, which are driven by increases from fossil electric power and transportation fuel requirements. Under the WRE 550 climate policy, industrial sector emissions growth declines after 2020 to levels much below current values. In the earlier decades, the direct emissions from the industrial sector decline at a faster rate than the overall global emission path, as seen by comparing Figure 12 to Figure 11. This result indicates that there are significant opportunities to reduce emissions in the US industrial sector that are less costly than in other sectors such as transportation. However, Figure 12 also shows that the

rate of reduction of direct industrial sector emissions slows significantly after 2050. This slowing reflects the difficulty in removing fossil fuels from industrial end-uses such as steam and process heat, as well as the cost in reducing feedstock and process CO_2 emissions as from sources such as cement and steel. After 2050 the bulk of industrial emissions reduction occurs indirectly, which reflects the mitigation of CO_2 emissions in the electric generation and refinery sectors.
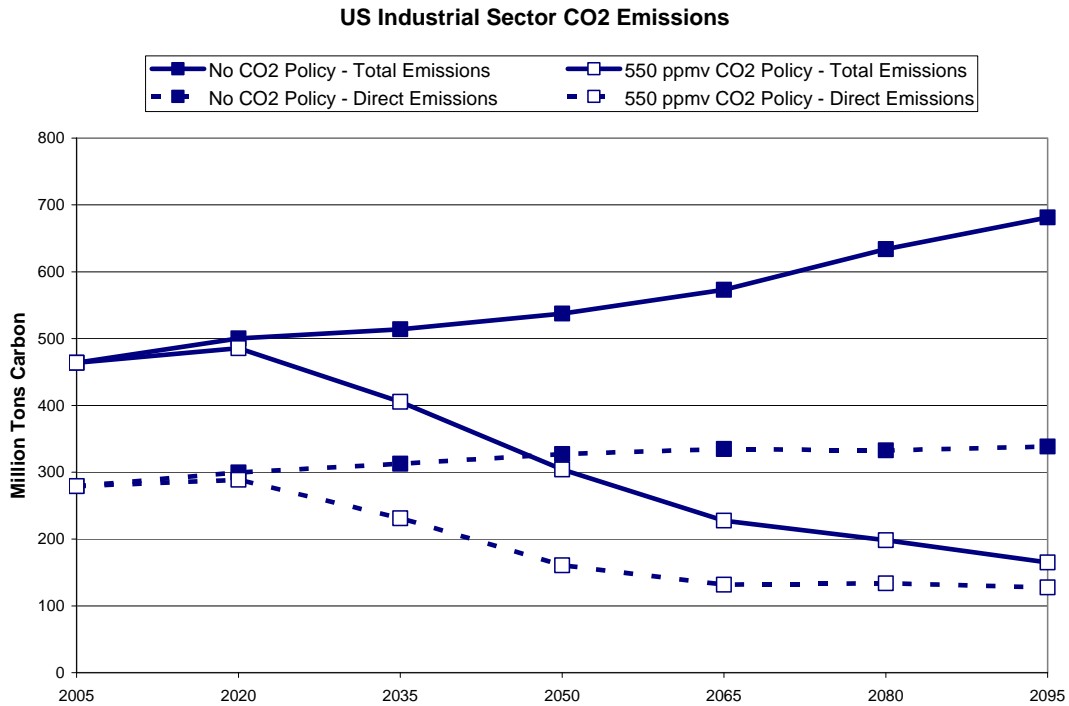
US Industrial Sector CO2 Emissions

Figure 12. Impact of WRE 550 CO$_2$ Policy on Industrial Sector Emissions

Figure 13 shows total carbon emissions (direct and indirect) by end-use energy sector for the reference and policy cases. In the reference case major increases in emissions from feedstocks and process energy use are seen across the century. Boilers, process heat, and feedstock use are major emitting categories. In the carbon constrained case emissions decrease significantly in all categories. The remaining emissions are largely residual direct emissions from sectors where it is either impractical or not economic to switch to low-carbon sources.
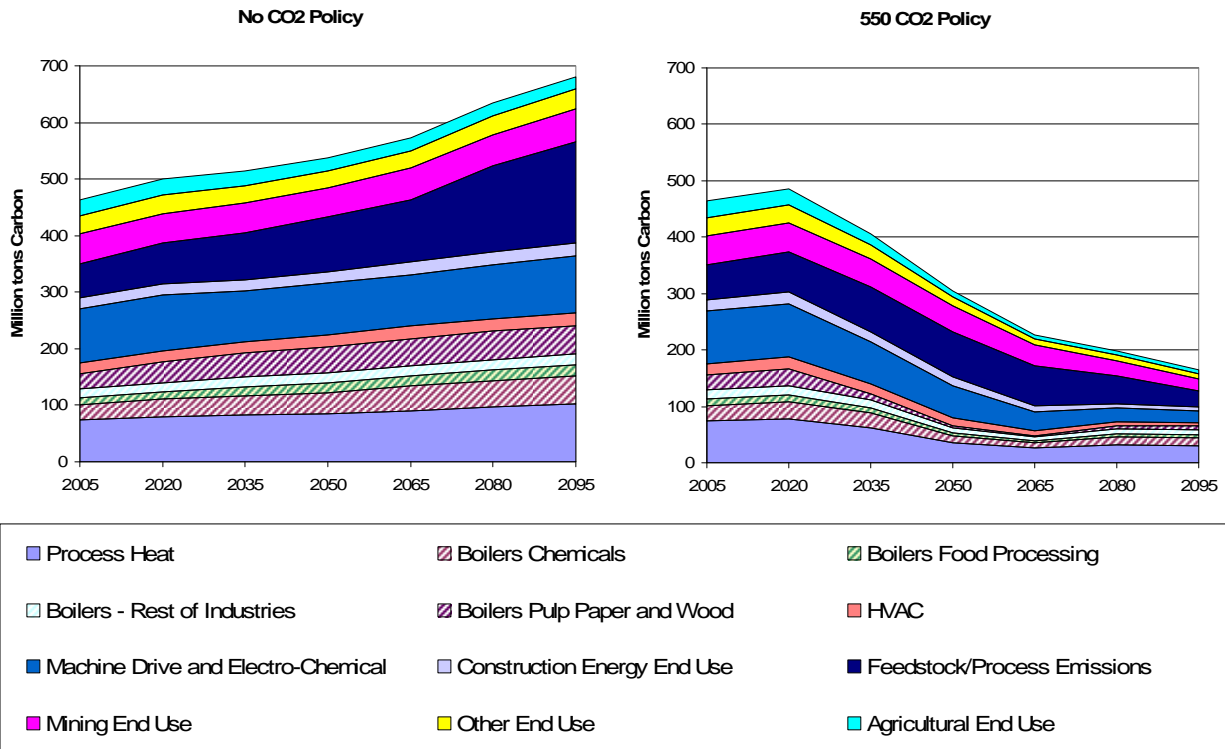
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Figure 13. Total CO$_2$ emissions by energy-end use under reference and climate policy cases

The fuel consumption that underlies the CO$_2$ emissions for these two cases is shown in Figure 14. Under the WRE 550 policy, coal is quickly driven down to levels needed as feedstocks, which may not result in CO$_2$ emissions. Biomass as a source of heat and steam replaces much of the coal used for this purpose. Oil consumption response is relatively small as much is for non-emitting feedstock use. Gas consumption does not change as much as coal since gas has a lower carbon content, although eventually the carbon price is high enough to reduce gas demand as well. A substantial electrification response is seen in the long term, although electricity can not economically supply all industrial energy services as there remains a need for intense sources of heat in some applications. While biomass combustion can fill some of the demand for low carbon or carbon-free steam, natural gas remains a competitive source of clean, dry process heat in some applications under the carbon price levels in this scenario.

A note about our treatment of biomass may be helpful. Biomass supply includes waste and residue sources, such as corn stover (e.g. corn stalks), and dedicated biomass crops such as switchgrass or hybrid poplar. All biomass is assumed to be carbon-neutral on a life-cycle basis, with no net emissions to the atmosphere.[5] While emissions occur at the point of combustion, these are offset when crops are growth to produce biomass (or residues). Note that biomass is used in the industrial sector in this model to produce steam or electricity. Minimal transformations are required, so this use cannot be compared directly to current corn ethanol production, where the net energy balance is quite different in.

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[5] Of course there will be energy required in gathering and transporting biomass, which would likely be met with non-carbon energy to the extent possible under a strict CO$_2$ policy.

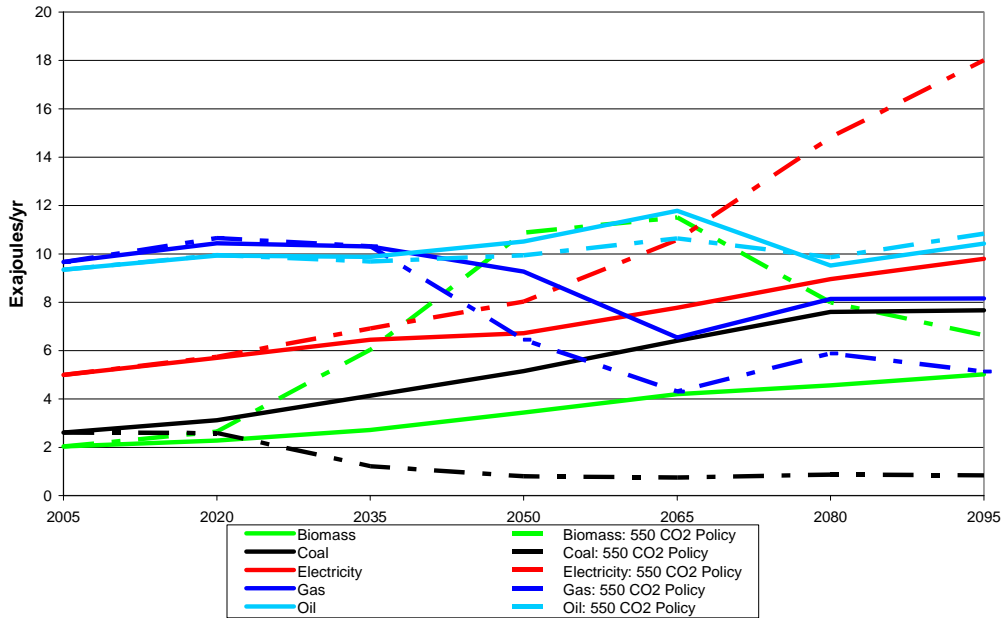**US Industrial Energy Consumption and a 550 ppm CO2 Policy**

Figure 14. Impact of WRE 550 CO₂ Policy on Industrial Sector Fuel Consumption

The biomass result under the CO_2 policy as shown in Figure 14 reveals an interesting dynamic between the industrial sector and the rest of the model. As a non-fossil (nearly zero carbon-emitting) fuel, biomass does not face a carbon price and is thus economically favored versus fossil fuels under the policy. In the policy case, biomass consumption rises sharply from 2020 to 2065. In the last periods, the trend reverses and biomass consumption declines even as carbon prices continue to rise. In a stand-alone model of the industrial sector, this result would seem anomalous. However in this integrated model, with all sectors facing the carbon price and increasing their demands for non-carbon energy sources, the emissions constraint and corresponding carbon price increases to the point at which becomes more economic to use biomass in other sectors such as transportation, which have fewer or costlier low-carbon options. The increased demand for biomass in other sectors increases its price along with the carbon price, and consequently it becomes relatively less economic to use biomass to provide industrial energy services. Biomass consumption in industry remains important in the long run, and is higher than in the no policy scenario. But some of it is replaced by an increase in electricity and an increase in gas consumption as well, even though gas consumption entails a carbon price penalty.

4.3 Technology Response to a CO₂ Policy: the Example of Cogeneration

Cogeneration is an interesting example of the technological response to a CO_2 policy and also illustrates the dynamics that result from feedbacks between the US industrial sector model and the rest of the economy. Model results for electricity cogenerated using natural gas in steam and heat applications and using biomass in steam applications is shown in Figure 15 both with and without the WRE 550 CO_2 policy. In the absence of a CO_2 policy, cogeneration from gas begins

a gradual decline as gas prices increase relative to the costs of central station electricity. In contrast, under the early years in the CO_2 policy, from 2020 through 2035, when carbon prices are at low to moderate levels, cogeneration using gas increases. Over this time period the increased efficiency that results in using gas to cogenerate electricity along with steam and heat results in a net economic benefit that offsets the carbon cost associated with the vented CO_2 from natural gas combustion. In the long run, however, the increasing price of natural gas plus the increasing carbon costs associated with natural gas combustion results in net costs for natural gas that are less favorable relative to electricity, and cogeneration using gas is lower than it would be without the carbon policy. Cogeneration from gas ultimately has to compete as a taxed fossil source versus non-fossil sources of electricity such as nuclear, wind, and solar. After carbon prices exceed a certain level, the economic decision tends more to using just the amount of gas needed for heat and steam demands and not burning the additional gas required to cogenerate electricity.
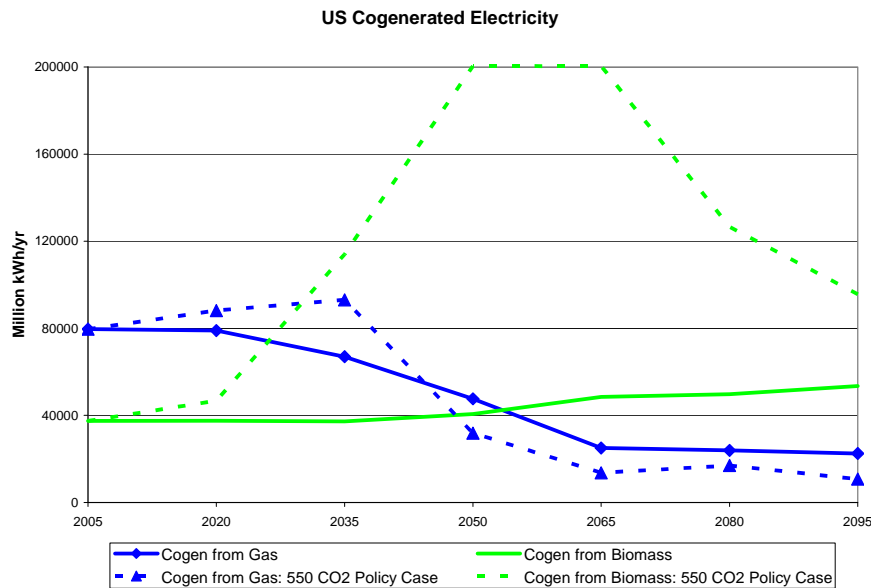

Figure 15. Impact of WRE 550 CO$_2$ policy on Industrial Cogeneration of Electricity

Electricity cogenerated from biomass gets a large boost from the carbon price as it is not taxed as a fossil fuel, and its cost relative to the electricity price in the market is favorable. In the long run, increasing biomass prices (from increased demands in other sectors such as transportation), reduce the use of cogenerated electricity from biomass relative to levels in mid-century. However, it remains a significant source of non-fossil heat and electricity, and its use in cogeneration application remains much higher in the policy case as compared to the no-policy case.

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5. Conclusions

This paper has examined the evolution of industrial energy demand in the United States over the next century and the potential response of the industrial sector to climate policies. The industrial model used here is embedded within the O^{bj}ECTS-MiniCAM integrated assessment model, which allows consistent feedbacks with the global economy in terms of fuel supplies, demands, and prices. The industrial sector was split into 12 industry groups and 7 end-use energy services, including feedstock use. This level of aggregation was chosen to be able to represent the dynamics of industrial energy demand responses to prices and policies, but at a level that remains tractable over a long time frame. This model allows the representation of explicit technologies and their impact on energy use and on the cost of climate policies.

When global emissions of CO_2 are constrained to follow a path leading to stabilization of CO_2 concentrations the industrial sector responds through increased electrification of energy services and shifting to the use of biomass. The extent of electrification, however, is limited because, even under a climate policy, electricity is not an economically attractive substitute for some boiler and process heat applications. Feedstock requirements in some industries might also still be met with fossil fuels, although biomass substitution might also be possible and needs to be further explored. These results indicate that physical and economic limits to electrification are important attributes of the industrial sector that need to considered in long-term scenarios. Consideration of these limits is an advance in the state of modeling industrial energy in a long-term integrated assessment model of global energy and climate like MiniCAM.

We find that energy price feedbacks play an important role in determining industrial sector fuel use, particularly under a climate policy. While use of biomass in cogeneration increases rapidly during the initial to mid-points of the carbon price path considered, the use of biomass co-generation decreases slightly in later years as biomass prices increase due to demand for biomass-derived fuels in other sectors. The competition with other sectors for biomass fuels in particular is an important attribute of attribute of this integrated modeling system.

This work represents our first look at a "hybrid approach" (Kim et al. 2006) to modeling the industrial sector within a long-term integrated modeling framework. Many improvements to this model are possible. Further work could include examination of the importance of process improvements that lower the overall need for energy services for production of the same good. Another goal is to link the demand for a number of the industrial sectors directly to fuel or agricultural good demands. Expansion of some industrial sectors to cover the globe may be possible where appropriate data is available.

A major limitation of this work is the availability and consistency of data on end-use technology costs. We have found in other sectors that differences in non-fuel costs for end-use technology can play an important role in technology choice and better information on energy-service costs would be useful in improving the industrial sector modeling.

6. Acknowledgements

7. References

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