Model Documentation Report: Industrial Demand Module of the National Energy Modeling System

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1. Introduction

This report documents the objectives and analytical approach of the National Energy Modeling System (NEMS) Industrial Demand Module (IDM). The report catalogues and describes model assumptions, computational methodology, parameter estimation techniques, and model source code. This edition of documentation is written for the NEMS version corresponding to the *Annual Energy Outlook 2018*.

This document serves three purposes. First, it is a reference document providing a detailed description of the NEMS Industrial Demand Module for model analysts, users, and the public. Second, this report meets the legal requirement of the U.S. Energy Information Administration (EIA) to provide adequate documentation in support of its models (Public Law 94-385, section 57.b2). Third, it facilitates continuity in model development by providing documentation from which energy analysts can undertake model enhancements, data updates, and parameter refinements in future projects.

Model summary

The NEMS Industrial Demand Module is a dynamic accounting model, bringing together representations of disparate industries and uses of energy in those industries and putting them in an understandable and cohesive framework. The IDM generates long-term (through the year 2050) projections of industrial sector energy demand as a component of the integrated NEMS. From NEMS, the IDM receives fuel prices, employment data, and the value of industrial shipments.

The NEMS Industrial Demand Module estimates energy consumption by energy source (fuels and feedstocks) for 15 manufacturing and 6 non-manufacturing industries. The manufacturing industries are classified as either energy-intensive manufacturing industries or non-energy-intensive manufacturing industries. The manufacturing industries are modeled through the use of detailed process flows or end-use accounting procedures. In addition some of the end-use models are modeled in somewhat more detail. The energy-intensive bulk chemicals industry is subdivided into four industry components, and the food industry is also subdivided into four components. There are detailed process flow submodules for the energy-intensive industries of cement and lime, aluminum, glass, iron and steel, and pulp and paper. The non-manufacturing industries are represented in less detail. The IDM projects energy consumption at the census region level; energy consumption at the census division level is allocated by using data from the State Energy Data System (SEDS) for 2017.[1] The national-level values reported in the *Annual Energy Review 2014* (AEO2014)[2] were allocated to the census divisions, also using the SEDS 2013 data.[1] The four census regions are divided into nine census divisions and are listed in Table 1. These census regions are also mapped in AEO2016.[3]

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[1] U.S. Energy Information Administration, *State Energy Data System Report 2013*, issued June 30, 2013, http://www.eia.gov/state/seds/.

[2] U.S. Energy Information Administration, *Annual Energy Review 2014*, DOE/EIA-384(2014), October 2011, http://www.eia.gov/totalenergy/data/annual/.

[3] U.S. Energy Information Administration, *Annual Energy Outlook 2016*, pp. F-1–F-2. http://www.eia.gov/forecasts/aeo/pdf/f1.pdf.

Table 1. Census regions and census divisions

Census region	Census divisions	States
1 (East)	1,2	Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont
2 (Midwest)	3, 4	Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, North Dakota, Nebraska, Ohio, South Dakota, and Wisconsin
3 (South)	5, 6, 7	Alabama, Arkansas, Delaware, District of Columbia, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, and West Virginia
4 (West)	8, 9	Arizona, Alaska, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2016*, http://www.eia.gov/forecasts/aeo/pdf/f1.pdf.

Unless otherwise noted, each manufacturing industry is modeled as three components: the process and assembly component (PA), the buildings component (BLD), and the boiler, steam, and cogeneration component (BSC). For the manufacturing industries, the PA component is separated into the major production processes or end uses. The non-manufacturing industries (agriculture, construction, and mining) have a different component structure. Agriculture PA includes the following components: irrigation, buildings, and vehicles. Construction includes buildings, civil engineering, and trade components. Mining includes vehicles and production components.

Archival media

The model is archived as part of the National Energy Modeling System production runs used to generate the AEO2016.

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Organization of this report

Chapter 2 discusses the purpose of the NEMS Industrial Demand Module, detailing its objectives, input and output variables, and the relationship of the IDM to the other modules of NEMS. Chapter 3 describes the rationale behind the IDM design, providing insights into further assumptions used in the model. The first section in Chapter 4 provides an outline of the model. The second section in Chapter 4 provides a description of the principal model subroutines, including the key computations performed and key equations solved in each subroutine.

The appendixes to this report provide supporting documentation for the IDM. Appendix A is the model abstract. Appendix B lists the input data for AEO2016. Appendix C provides industrial group descriptions. Appendix D is a bibliography of data sources and background materials used in model development.

2. Model Purpose

The National Energy Modeling System (NEMS) Industrial Demand Module (IDM) was designed to project industrial energy consumption by fuel type and industry as defined in the North American Industrial Classification System (NAICS).[4] The IDM generates long-term (through the year 2050) projections of industrial sector energy demand as a component of the integrated NEMS. From the other components of NEMS, the IDM receives fuel prices, employment data, and the value of shipments, which are expressed in 2012 dollars, for industrial activity. Based on the values of these variables, the IDM passes back to NEMS estimates of fuel consumption for 17 main fuels, including feedstocks and renewables (Figure 1) for each of 21 industry groups. The IDM projects energy consumption at the census region level; energy consumption is allocated to the census division-level based on the latest State Energy Data System (SEDS) data.

Figure 1. Industrial Demand Module interactions within the National Energy Modeling System (NEMS)
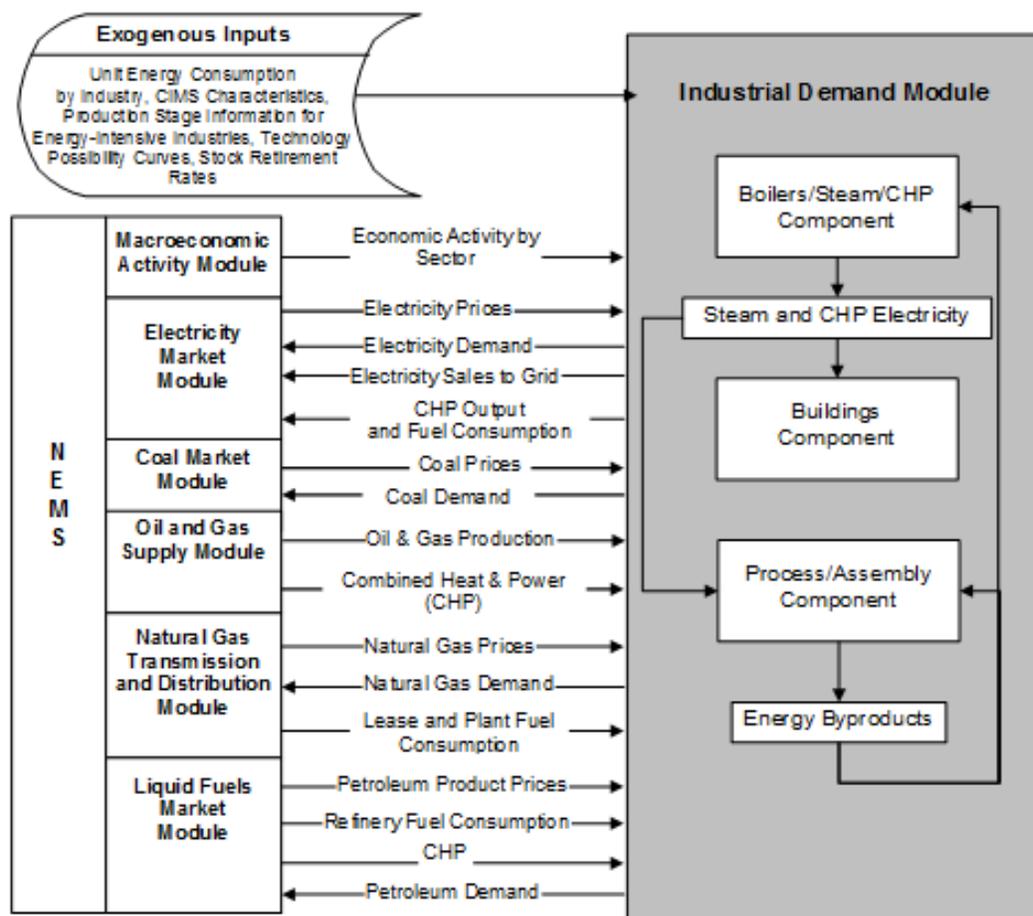
Source: U.S. Energy Information Administration

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[4] Executive Office of the President, Office of Management and Budget, *North American Industry Classification System, United States, 2012* (Washington, DC, 2012).

Figure 1 shows the IDM inputs from and outputs to other NEMS modules. The IDM is activated one or more times during the processing for each year of the projection period by the NEMS Integrating Module. On each occurrence of module activation, the processing flow follows the outline shown in Figure 1. Note that all inter-module interactions must pass through the Integrating Module. For the IDM, the Macroeconomic Activity Module (MAM) is critical. The MAM supplies industry value of shipments and employment for the IDM subsectors. Ultimately, these two drivers are major factors influencing industrial energy consumption over time. The second most important influencing factor is the set of energy prices provided by the various supply modules.

Projected industrial sector fuel demands generated by the IDM are used by NEMS in the calculation of the supply and demand equilibrium for individual fuels. In addition, the NEMS supply modules use the industrial sector outputs in conjunction with other projected sectoral demands to determine the patterns of consumption and the resulting amounts and prices of energy delivered to the industrial sector.

The IDM is an annual energy model and, as such, does not project seasonal or daily variations in fuel demand or fuel prices. The model was designed primarily for use in applications such as the *Annual Energy Outlook* (AEO) and other analyses of long-term energy-economy interactions.

The model can also be used to examine various policy, environmental, and regulatory initiatives. For example, energy consumption per dollar of shipments is, in part, a function of energy prices. Therefore, the effect on industrial energy consumption of policies that change relative fuel prices can be analyzed endogenously in the model.

The IDM can also endogenously analyze specific technology programs or energy standards. The model distinguishes among the energy-intensive manufacturing industries, the non-energy-intensive manufacturing industries, and the non-manufacturing industries. Variation in the level of representational detail and other details of IDM model structure affect the suitability of the model for specific analyses.

3. Model Rationale

Theoretical approach

The Industrial Demand Module (IDM) can be characterized as a dynamic accounting model, combining economic and engineering data and knowledge. Its architecture brings together representations of the disparate industries,[5] and uses of energy in those industries, combining them in an understandable and cohesive framework. An explicit representation of the varied uses of energy in the industrial sector is used as the framework on which to base the dynamics of the model.

One of the overriding characteristics of the industrial sector is the heterogeneity of industries, products, equipment, technologies, processes, and energy uses. Adding to this heterogeneity is the inclusion in this sector of not only manufacturing but also the non-manufacturing industries of agriculture, mining, and construction. These disparate industries range widely from highly energy-intensive activities to non-energy-intensive activities. Energy-intensive industries are modeled at a disaggregate level so that projected changes in composition of the products produced will be automatically taken into account when computing energy consumption.

Modeling approach

A number of considerations have been taken into account in building the IDM. These considerations have been identified largely through experience with current and earlier U.S. Energy Information Administration (EIA) models, with various EIA analyses, through communication and association with other modelers and analysts, as well as through literature review. The primary considerations are listed below.

The IDM incorporates three major industry categories, consisting of energy-intensive manufacturing industries, non-energy-intensive manufacturing industries, and non-manufacturing industries. The level and type of modeling and the attention to detail is different for each.

Each manufacturing industry is modeled using either an end-use model approach or a process-flow model approach. End-use models use three separate but interrelated components, consisting of buildings (BLD), process and assembly (PA), boiler, steam, and cogeneration (BSC) activities. Process-flow models include a BLD component and a PA component. For aluminum, iron and steel, and paper, the BSC component is modelled within the PA component.

The end-use models use a capital stock vintage accounting framework that models energy use in new additions to the stock and in the existing stock. The existing stock is retired based on retirement rates for each industry.

The manufacturing industries are modeled with a structure that explicitly describes the major process flows or major consuming uses in the industry:

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[5] According to the 2007 North American Industry Classification System, there are 596 industries classified as industrial by NEMS.

o The IDM uses technology choice to characterize technological change. Manufacturing industries are modeled using a process-flow model that allows for changes in technology over time. The cement and lime, aluminum, glass, iron and steel, and pulp and paper industry models have been expanded to use technology data found in the Consolidated Impacts Modeling System (CIMS) and allow for more detailed technology modeling.

o For other industries, specific technology data may be defined for each production process step or end use, but currently all other industries use the end-use model approach. Technology improvement for each technology bundle for each production process step or end use is based on engineering judgment.

The model structure accommodates several industrial sector activities, including fuel switching, cogeneration, renewables consumption, recycling, and byproduct consumption. For the end-use models the principal model calculations are performed at the census region level and aggregated to a national total. For the process-flow models, the model calculations are done at the national level and parsed out to the census regions based on regional macroeconomic data.

Industry categories

The industrial sector consists of numerous heterogeneous industries, as shown in Table 2. Each industry is associated with one or more NAICS codes. (NAICS is the North American Industrial Classification System.) The IDM classifies these industries into three general groups: energy-intensive manufacturing industries, non-energy-intensive manufacturing industries, and non-manufacturing industries. There are eight energy-intensive manufacturing industries, of which seven are modeled in the IDM: food products; paper and allied products; bulk chemicals; glass and glass products; cement and lime; iron and steel; and aluminum. Also within the manufacturing group are eight non-energy-intensive manufacturing industries: metal-based durables, consisting of fabricated metals; machinery; computers and electronics; electrical equipment and appliances; transportation equipment; wood products; plastic and rubber products; and the balance of manufacturing. The industry categories are also chosen to be as consistent as possible with the categories that are available from *the 2014 Manufacturing Energy Consumption Survey* (2014 MECS).

Table 2. Industries, NAICS Codes, and IDM industry codes

Industry	NAICS code (North American Industrial Classification System)	Industrial Demand Module (IDM) industry code
Energy-intensive manufacturing		
Food products	311	7
Grain and oilseed milling	3112	
Dairy product manufacturing	3115	
Animal/seafood processing	3116, 3117	
Other food products	311 not elsewhere classified	
Paper and allied products	322	8
Bulk chemicals	Portions of 325	9
Organic (NAICS 32511, 32519)	325110, 32519	
Inorganic	325120–325180	
Resins (NAICS 3252)	3252	
Agricultural (NAICS 3253)	3253	
Glass and glass products	3272, 327993	10
Cement and lime	327310, 327410	11
Iron and steel	331110, 3312, 324199	12
Aluminum	3313	13
Non-energy-intensive manufacturing		
Metal-based durables	332–336	
Fabricated metals	332	14
Machinery	333	15
Computers and electronics	334	16
Electrical equipment, appliance, and components	335	18
Transportation equipment	336	17
Wood products	321	19
Plastic and rubber products	326	20
Balance of manufacturing	312–316, 323, 3254–3256, 3259, 3271, 327320, 327330, 327390, 327420, 233279, 3314, 3315, 337, 339	21
Non-manufacturing industries		
Agriculture, crop production, and support	111,1151	1
Agriculture, other	112, 113, 1152, 1153	2
Coal mining	2121	3
Oil and natural gas extraction	211	4
Metal and non-metallic mining	2122, 2123	5
Construction	23	6

NAICS = North American Industry Classification System (2012).

The eighth energy-intensive industry, petroleum refining (NAICS 32411), is modeled in detail in the Liquid Fuels Market Module (LFMM), a separate module of NEMS, and the projected energy consumption from LFMM is included in the manufacturing total. The projections of lease and plant fuel and cogeneration consumption for Oil and Gas (NAICS 211) are modeled in the Oil and Gas Supply Module and reported in the industrial sector energy consumption totals. These industry groupings facilitate model design and data processing. The primary consideration is the distinction between energy-intensive groups and non-energy-intensive industry groups. The industry categories are also chosen to be as consistent as possible with the categories that are available from 2014 MECS. Of the manufacturing industries, seven of the most energy-intensive are modeled in greater detail in the IDM.

Energy sources modeled

The IDM estimates energy consumption by 21 industries for 14 primary and secondary energy sources, some of which have nonfuel uses. The energy sources modeled in the IDM are as follows:

Sources used in fuel applications:

- o Purchased electricity
- o Natural gas
- o Steam coal
- o Distillate oil
- o Residual oil
- o Natural gas liquids (NGL) for heat and power (NGL is sometimes reported as liquefied petroleum gas)
- o Motor gasoline
- o Renewables, specifically biomass and hydropower
- o Coking coal (including net imports)
- o Petroleum coke

Sources used in nonfuel applications:

- o Natural gas feedstock
- o NGL feedstock
- o Petrochemical feedstock
- o Asphalt and road oil

In the model, byproduct fuels, such as residual fuel oil or petroleum coke, are always consumed before purchased fuels. "Miscellaneous petroleum" in the industrial sector is a residual composite of minor petroleum fuels subject to wide variations due to changing reassessments of petroleum coke, still gas, and naphtha feedstock for petrochemicals.

Renewable fuels are modeled in the same manner as all other fuels in the IDM. Renewable fuels are modeled both in the PA component and in the boiler, steam, and cogeneration (BSC) component. The primary renewable fuels consumed in the industrial sector are pulping liquor (a byproduct of the chemical pulping process in the paper industry) and wood.

Recycling

With higher projected landfill costs, regulatory emphasis on recycling, and potential cost savings, recycling of post-consumer scrap is likely to grow. Projecting such growth, however, is highly dependent on regulatory assumptions, the growth of the economy, and issues related to the quality of recycled materials. Secondary processing of aluminum is now modeled in the Aluminum Industry submodule as a process flow and investment option. Iron-and-steel and pulp-and-paper process flow models consider recycling in detail.

Industrial model structure

Figure 2. Basic Industrial Demand Module structure[6]
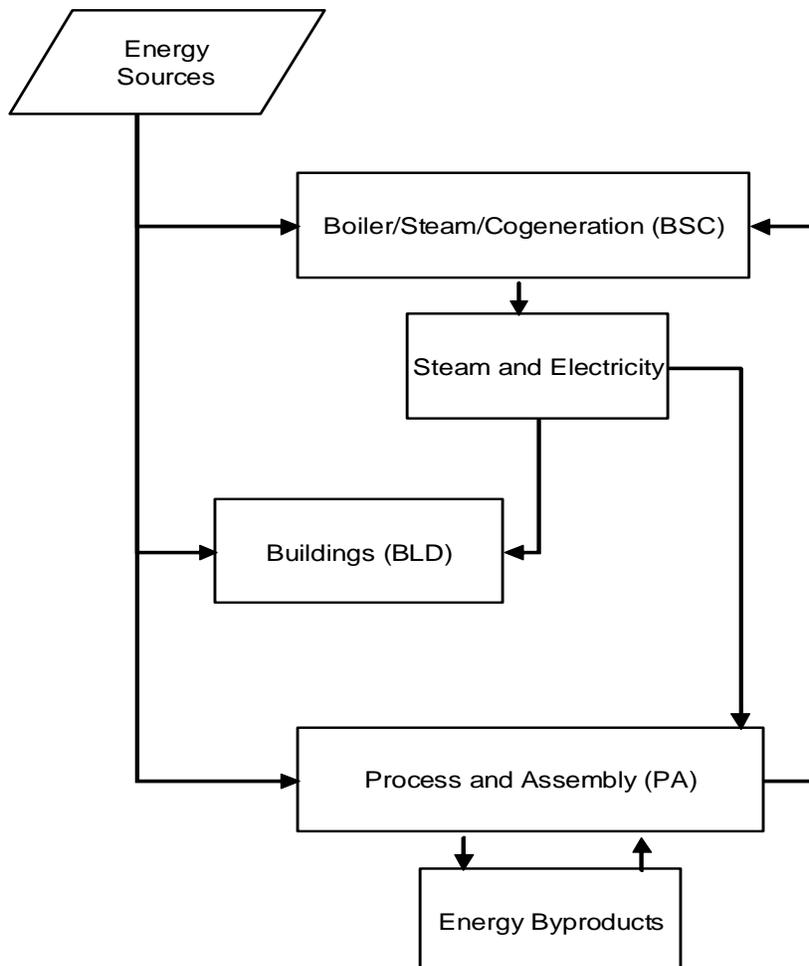
Source: U.S. Energy Information Administration

For each industry, the flow of energy among the three model components is represented by the arrows in Figure 2. The boiler, steam, and cogeneration (BSC) component satisfies the steam demand from the PA and BLD components. For the manufacturing industries, the PA component is broken down into the major production processes or end uses. Energy consumption in the IDM is primarily a function of the level of industrial economic activity. Industrial economic activity in NEMS is measured by the dollar value of shipments (in constant 2012 dollars) produced by each industry group. The value of shipments by industry (by NAICS code) is provided to the IDM by the NEMS Macroeconomic Activity Module. As the level of industrial economic activity increases, energy consumption typically increases, but at a slower rate than the growth in economic activity.

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[6] Process-flow industries model the boiler, steam, and cogeneration component within the process and assembly component.

The amount of energy consumption reported by the IDM is also a function of the vintage of the capital stock that produces the shipments. The end-use models assume that new capital stock will consist of state-of-the-art technologies that are, on average, more energy efficient than the existing capital stock. Consequently, the amount of energy required to produce a unit of output using new capital stock is less than that required using the existing capital stock. The energy intensity of the new capital stock relative to 2014 capital stock is represented by a parameter called a technology possibility curve (TPC), which is estimated for each process step or end use. These TPCs are based on engineering judgments about the likely future path of energy intensity changes. The only exceptions to this methodology are the process and assembly calculations for the cement and lime, aluminum, glass, iron and steel, and pulp and paper industries, which use 2014 capital stock estimates and then estimate the technology choice associated with new capital stock (related to retirement of existing capital stock) and increases in capital stock (related to increasing shipments). Capital stock for the year 2014 is used because it is based on survey data from the *2014 Manufacturing Energy Consumption Survey* (2014 MECS), the most recently available survey.

The energy intensity of the existing capital stock for the end-use models is assumed to decrease over time, but not as rapidly as the assumed decrease in new capital stock. The decline is due to retrofitting and replacement of equipment from normal wear and tear. Retrofitting existing capacity is assumed to incorporate 50% of the improvement that is achieved by installing new capacity. The process flow models select less energy-intensive technology based on fixed costs, fuel costs, and emissions associated with new capital stock. The net effect is that over time the amount of energy required to produce a unit of output declines. Although total energy consumption in the industrial sector is projected to increase, overall energy intensity is projected to decrease.

Energy consumption in the buildings component is assumed to grow at the same rate as the average growth rate of employment and output in that industry. This formulation has been used to account for the countervailing movements in manufacturing employment and value of shipments. Manufacturing employment falls over the projection, which alone would imply falling building energy use. Because shipments tend to grow fairly rapidly, conditioned floor space is assumed to increase. Energy consumption in the boiler, steam, and cogeneration (BSC) component is assumed to be a function of the steam demand of the other two components.

Technology possibility curves, unit energy consumption, and relative energy intensities for end-use models

The key computations of the Industrial Demand Module end-use models are the unit energy consumption (UEC) estimates made for each NAICS industry group. UEC is defined as the amount of energy required to produce either one dollar's worth of shipments or one unit of physical output. The distinction between existing and new capital equipment is maintained with a vintage-based accounting procedure. In practice, the fuel use in similar capital equipment is the same across vintages. For example, an electric arc furnace primarily consumes electricity no matter whether it is an old electric arc furnace or a new one.

The modeling approach incorporates technical change in the production process to achieve lower energy intensity. Autonomous technical change can be envisioned as a learning-by-doing process for existing technology. As experience is gained with a technology, the costs of production decline. Autonomous technical change is assumed to be the most important source of energy-related changes in the IDM. Few industrial innovations are adopted solely because of their energy consumption characteristics, but rather for a combination of factors, including process changes to improve product quality, changes made to improve productivity, or changes made in response to the competitive environment. These strategic decisions are not readily amenable to economic or engineering modeling at the current level of disaggregation in the IDM. Instead, the IDM is designed to incorporate overall changes in energy use on a more aggregate and long-term basis using the autonomous technical change parameters.

TPCs are used to derive future improvements in unit energy consumption. Future energy improvements are estimated for old (retrofit) and new processes and facilities. The energy improvements for grouped old facilities consist of gradual improvements due to energy conservation measures, retrofits of selected technologies, and the closure of older facilities, leaving the more-efficient plants in operation. The energy savings for old processes and facilities are estimated using engineering judgment regarding how much energy savings could be reasonably achieved in each industry. The estimated annual energy savings for each energy conservation measure are up to 0.5% per year.

UEC values for the state-of-the-art (SOA) and advanced technologies are also estimated. SOA technologies are the latest proven technologies that are available at the time a commitment is made to build a new plant. These values are then compared with the 2014 UEC values to develop an index of relative energy intensity (REI). Relative energy intensity is defined as the ratio of energy use in a new or advanced process compared with 2014 average energy use.

The efficiency improvement for new facilities assumes that the installation includes the SOA technologies available for that industry. A second, and at times more important, set of substantial improvements can occur when advanced technologies become available for a specific process. Often one sees a number of technologies being developed and it is difficult to ascertain which specific technologies will be successful. Judgment is necessary as to the energy-saving potential and the likelihood for such savings to be realistically achieved. All energy improvements in the IDM are based on 2014 energy usage.

In addition, even SOA technologies and advanced technologies can sometimes be expected to improve after development as the process is improved, optimal residence times and temperatures are found, and better energy recovery techniques are installed. Depending on the process, these considerations are factored into the projections as slow improvements ranging from zero to a maximum of just under 1% per year.

Old facilities are assumed to be able to economically justify some retrofits and, for other reasons listed above, show slow improvements over time in their unit energy consumption. It is assumed that by 2050, old equipment (that is, the 2014 stock) still operating can achieve up to 50% of the energy savings of SOA technology due to retrofits and other reasons listed above. Thus, if SOA technology has an REI of 0.80, old equipment operating in the year 2050 will have an REI of 0.90. As a convenience for modeling purposes, the rate of change between the initial and final points is defined as the TPC and used to interpolate for the intervening points.

Advanced technologies are ones that are still under development and will be available at some time in the future. It is uncertain which specific technologies will be implemented, but it can be assumed that at least one of these technologies or a similar technology will be successful. It is also recognized that in some instances thermodynamic limits are being approached, which will prevent further significant improvements in energy savings.

Industrial energy consumption is affected by increased energy efficiency in new and old plants, the growth rate of the industry, and the retirement rate for old plants. The efficiency changes are captured in the TPC's and the rate of growth is given by the MAM.

For all industries except process flow industries,[7] the IDM capital stock is grouped into three vintages: old, middle, and new. The old vintage consists of capital in production in 2014 and is assumed to retire at a fixed rate each year. Middle vintage capital is that which is added from 2014 through the year *Year-1*, where *Year* is the current projection year. New capital is added for the projection years when existing production is less than the output projected by the MAM. Capital stock added during the projection period is retired in subsequent years at the same rate as the pre-2014 capital stock. Details of the calculation of UECs can be found in the description of CALCSC, which is on page 81.

Buildings component UEC

Buildings are estimated to account for a small percentage of allocated heat and power energy in manufacturing industries in general, but some non-energy intensive manufacturing industries have a significant percentage of building energy use.[8] Detailed projections of manufacturing sector building energy consumption are available upon request from the model contact person listed on page 2. Energy consumption in manufacturing buildings is assumed to grow at the average of the growth rates of employment and shipments in that industry. This assumption appears to be reasonable because lighting

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[7] The process flow industries are cement and lime, aluminum, glass, iron and steel, and pulp and paper.
[8] U.S. Energy Information Administration, 2014 *Manufacturing Energy Consumption Survey*, (http://www.eia.gov/consumption/manufacturing/), March 2013. Note that byproduct and non-energy use of combustible fuels are excluded from the computation because they are not allocated in the MECS tables.

and heating, ventilation, and air conditioning (HVAC) are designed primarily for workers rather than machines. However, because the value of shipments tends to grow, it is likely that conditioned floor space also grows. The IDM uses an average to account for the contrasting trends in employment and shipment growth rates.

Process and assembly component UEC

The process and assembly (PA) component is the largest share of direct energy consumption. To derive energy use estimates for the process steps, the production process for each industry was first decomposed into its major steps, and then the engineering and product flow relationships among the steps were specified. Process steps for each industry were analyzed using one of the following two methodologies:

Process flow industries. Based on the approach used in the Consolidated Impacts Modeling System (CIMS),[9] the PA component is first broken down into several unit operations using process engineering techniques. The energy consumed by each unit operation and the corresponding mass flow of material (raw materials, intermediates, or final products) through that unit operation are calculated from data in the base year. Energy consumption projections in subsequent years are based on shipments, the amount of capacity at each process step needed to meet demand, technology used in each process step, and energy consumption of each technology. This approach is applied to model those industries where the process flows can be well defined for a single broad product line by unit process step: glass, cement and lime, aluminum, iron and steel, and pulp and paper.

End-use industries. Develop end-use estimates of energy use by generic process unit as a percentage of total energy use in the PA component. This is used where the diversity of end products and unit processes is relatively large: food products, bulk chemicals, metal-based durables, plastic products, wood products, and the balance of manufacturing. A motor stock model, which is described on page 16, calculates the electricity consumption for the machine drive end use for these five industries or industry groups.

In both methodologies, major components of energy consumption are identified by process for various energy sources, including the following:

- o Fossil fuels
- o Liquids (petroleum, natural gas liquids)
- o Natural gas
- o Coal
- o Purchased electricity (valued at 3,412 British thermal units [Btu] per kilowatthour [kWh]);
- o Steam
- o Non-fuel energy sources, such as chemical feedstocks and asphalt

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[9] Roop, Joseph M. and Chris Bataille, "Modeling Climate Change Policies in the US and Canada: A Progress Report" Presentation to the 26th USAEE/IAEE North American Conference September 27, 2006 (http://www.usaee.org/USAEE2006/papers/josephroop.pdf)

The following sections present a more detailed discussion of the process steps and UEC estimates for each of the energy-intensive industries. The data tables showing the estimates are presented in Appendix B and are referenced in the text as appropriate. The process steps are model inputs with the variable name INDSTEPNAME.

Motor stock model

Electricity consumption by the machine drive end use for the food, bulk chemicals, metal-based durables, and balance of manufacturing industries is modeled differently than for the other end uses in these industries. Instead of using the TPC approach described above, a motor stock model calculates machine drive electricity consumption. Subroutine MOTORS, described on page 50, calculates electricity use for motors. Seven motor size groups are modeled for each industry, as shown in Table 3.

Table 3. Motor categories by horsepower

Horsepower (hp)
1–5 hp
6–20 hp
21–50 hp
51–100 hp
101–200 hp
201–500 hp
More than 500 hp

Source: Industrial Demand Module

The data for the basic motor stock model were derived from *United States Industrial Electric Motor Systems Market Opportunities Assessmen*t,[10] a report produced for the U.S. Department of Energy's Office of Industrial Technologies. Section 313 of *The Energy Independence and Security Act of 2007* (EISA2007) increased the minimum efficiency of motors to reflect the National Electrical Manufacturers Association's Premium Efficiency requirements, effective no later than 2011. These revised standards simplify the model code since only premium-efficiency motors can be purchased.

The motor stock model can be broken down into several steps. The steps are outlined as follows:

- o Evaluating rewind or replace decision for failed motors.
- o For each failed motor, evaluating whether the motor is repaired or replaced. The cost and performance characteristics for the motor options are from the MotorMaster + version 4.0 software.
- o Determining the cost differential for replacing the motor, which is the difference between the cost of the new motor meeting minimum efficiency standards and the cost of repairing the motor.

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[10] U.S. Department of Energy, United States Industrial Electric Motor Systems Market Opportunities Assessment (Burlington, MA, December 1998).

- o Determining the annual electricity expenditure savings from replacing the motor. This calculation requires the rated motor horsepower, the average motor part-load, the conversion factor from horsepower to kilowatts, the annual operating hours for the motor, the industrial electricity price, the efficiency rating for a minimum efficiency motor, and the efficiency rating for a repaired motor. For purposes of the analysis, the electricity price is assumed to remain constant at the level in the year the choice is made.

- o Determining the payback period needed to recover the cost differential for replacing the motor. The payback is determined by dividing the new motor cost differential by the annual electricity expenditure savings.

- o Assessing the market penetration for replacement motors based on the payback period and the payback acceptance curve.

- o Estimate annual change in industry motor stock and industry motor efficiency as a result of rewinds and replacements.

- o Given the payback for each motor size group in each industry, estimating the fraction of replacement motors purchased. This analysis begins with an assumed distribution of required investment payback periods, deemed the payback acceptance curve. In the table, for each integer payback period from zero to four years, a fraction of new motors is specified. This process quantifies the notion that the shorter the payback, the greater the fraction of firms that would choose the higher efficiency option, in this case replacing a failed motor.

- o Determining the number of new motors purchased as a result of replacements. This is the difference between the total number of motors failed and the number of motors rewound.

- o Determining the change in the motor stock for the year. Tracking the number, vintage, and condition of motors in the stock is necessary for calculating average efficiency and average electricity consumption for the machine drive end use.

- o Given the value of shipments growth for each industry and the number of new motors purchased to replace failed motors, calculating total purchases of new motors for each size group within each industry can be determined. The new motors will have a higher efficiency than the beginning stock.

- o Given the assumed failure rate for the beginning stock of motors and the number of failed motors replaced, determining the number of rewound motors for each size group within each industry can be determined. Rewinding typically reduces the efficiency of motors.

- o Calculating the average efficiency of the end-of-year motor stock and the average electricity consumption for machine drive.

- o Determining the average electricity consumption and efficiency for the motor stock as a weighted average of the electricity consumption for new premium efficiency motors, rewound motors, and surviving motors.

- o Calculating the total electricity consumption for machine drive and the effect of system efficiency improvements. Efficiency improvements in the machine drive end use may be

accomplished by modifying the system within which the motor operates as well as by choosing a more efficient motor.

  o   Determining the total electricity consumption for the motor stock from the stock of motors and the average efficiency.

  o   Determining the adjusted total electricity consumption for the motor stock. Several parameters may be modified to reflect the assumptions on how the motor systems will change. There are three main types of motor systems: pump systems, fan systems, and compressor systems. For each of these types, there is a parameter that represents the total percentage of motor systems within an industry by type, and one for the amount by which the system efficiency can be improved.

Boiler, steam, cogeneration component

The BSC component of the IDM projects consumption of energy to meet the steam demands from the other two components and to provide internally generated electricity to the buildings and process-and-assembly components for all industries except iron-and-steel and pulp-and-paper, for which consumption is calculated in the PA step. The BSC component calculates the consumption of fuels and renewable energy to produce the steam and, in appropriate situations, cogenerate electricity.

The use of fuels to produce both heat and electric power in a single unit, the cogeneration element of the BSC component, represents technology implemented in industry for efficiency, which also provides a financial benefit. Some industries have been operating cogeneration plants for more than 40 years; however, due to various incentives and barriers during periods of scarce capital, varying interest rates, and changes in product demands, the popularity of cogeneration has grown and declined historically.

The modeling approach in the IDM captures both the benefits and risks in determining new capacity, because a well-developed understanding of industrial steam generation is critical, especially under changing outlooks for natural gas and electricity supply and price to industrial end users.

The steam demand and byproducts from the PA and BLD components are passed to the BSC component, which allocates the steam demand to conventional boilers and to cogeneration. The allocation is based on an estimate of useful thermal energy supplied by cogeneration plants. Energy for cogeneration is subtracted from total indirect fuel use as reported in MECS to obtain conventional boiler fuel use and the associated steam. Assumed average boiler efficiency and a fuel-sharing equation are used to estimate the required energy consumption to meet the steam requirement from conventional boilers.

The boiler fuel share variable, $ShareFuel_f$, is calculated by fuel using a logistic formulation based on data from the 2014 MECS. Waste and byproduct fuels are excluded from the equation because they are assumed to be consumed first. Details of the $ShareFuel_f$ calculation are given on page 82.

Cogeneration capacity, generation, fuel use, and thermal output are determined from exogenous data, and new additions are simulated, as needed, using endogenous engineering and economic evaluation. Existing cogeneration capacity and planned additions are based on data collected on EIA's Form 860 and predecessor surveys. The most recent data used are for 2014, with planned additions (units under construction) through 2016.

The above data are processed outside the IDM to separate industrial cogeneration from commercial sector cogeneration, cogeneration from refineries and enhanced oil recovery operations, and offsite cogeneration. Offsite cogeneration units are primarily merchant power plants selling to the grid, often supplying relatively small amounts of thermal energy available for industrial uses. Cogeneration capacity is disaggregated by region and industry: the four IDM industries that use the most cogeneration are bulk chemicals, paper, food, and iron and steel. Refining is also a major cogeneration industry, but it is not modeled in the IDM. The iron-and-steel and pulp-and-paper submodules do not use this general model component that applies to all other industry models, but they have specific cogeneration modeling.

The modeling of unplanned cogeneration begins with model year 2015, under the assumption that planned units under construction cover only some of the likely additions through 2014. In addition, it is assumed that any existing cogeneration capacity will remain in service throughout the projection, or equivalently, will be refurbished or replaced with like units of equal capacity. The modeling of unplanned capacity additions is done for two capacity types: biomass-fueled and fossil-fueled. Biomass cogeneration is assumed to be added as increments of biomass waste products are produced, but the iron-and-steel and pulp-and-paper submodules have specific cogeneration code. The amount of biomass cogeneration added is equal to the quantity of new biomass available (in Btu), divided by the total heat rate assumed from biomass steam turbine cogeneration.

Unplanned additions to fossil-fueled cogeneration are projected based on an economic assessment of capacity that could be added to generate the industrial steam requirements that are not already met by existing cogeneration. The driving assumption is that the technical potential for traditional cogeneration is primarily based on supplying thermal requirements. We assume that cogenerated electricity can be used to either reduce purchased electricity or it can be sold to the grid. For simplicity, the approach adopted is generic and the characteristics of the cogeneration plants are set by the user. The fuel used is assumed to be natural gas, based on a study performed for EIA.[11]

The steps to the approach are outlined as follows:

- o Assessing the steam requirements that could be met by new cogeneration plants
- o Subtracting steam met by existing cogeneration units, given total steam load for the industry in each region from the process-assembly and buildings components
- o Classifying non-cogenerated steam uses into six size ranges, or load segments, based on an exogenous data set[12] providing the boiler size distribution for each industry and assuming that steam loads are distributed in the same proportions as boiler capacity. Also obtained from the same exogenous data set is the average boiler size (in terms of fuel input per hour) in each load segment, which is used to size the prototypical cogeneration system in each load segment. The prototype cogeneration system sizing is based on the steam generated by the average-sized boiler in each load segment

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[11] Leidos, Review of Distributed Generation and Combined Heat and Power Technology Performance and Cost Estimates and Analytic Assumptions for the National Energy Modeling System, report prepared for the Office of Energy Consumption and Efficiency Analysis, U.S. Energy Information Administration, Washington, DC, May 2016.

[12] Energy and Environmental Analysis, Inc., *Characterization of the U.S. Industrial Commercial Boiler Population*, submitted to Oak Ridge National Laboratory, May 2005.

- o Establishing the average hourly steam load in each segment from the aggregate steam load to determine total technical potential for cogeneration (discussed further below)
- o Evaluating a natural gas turbine system prototype for each size range
- o Establishing a candidate cogeneration system for each load segment with thermal output that matches the steam output of the average-sized boiler in each load segment, with user-supplied characteristics for eight cogeneration systems for either the Reference case or the High Technology case. The characteristics used in the calculation include the following:
  - Net electric generation capacity in kilowatts
  - Total installed cost, in 2005 dollars per kilowatthour—electric
  - System capacity factor
  - Total fuel use per kilowatthour
  - Fraction of input energy converted to useful heat and power
- o Determining the investment payback period needed to recover the prototypical cogeneration investment for each of the system sizes
- o Assessing market penetration based on the discounted payback and the payback acceptance curve
- o Determining the maximum technical potential for cogeneration under the assumption that all non-cogeneration steam for each load segment is converted to cogeneration. This process assumes that the technical potential is based on 1) sizing systems, on average, to meet the average hourly steam load in each load segment and 2) the power-steam ratio of the prototype cogeneration system
- o Determining economic potential and market penetration of the candidate cogeneration systems
- o Estimating the fraction of total technical potential that is considered economical, given the payback for the prototype system evaluated. Doing this requires starting with an assumption about the distribution of required investment payback periods called the payback acceptance curve. The shorter the payback, the greater the fraction of firms that would be willing to invest. It can also capture the effect that market barriers have in discouraging cogeneration investment
- o Estimating the estimate the amount of capacity that would be added in the current model year, given the total economic potential for cogeneration. The annual capacity additions are estimated assuming linear market penetration over a 20-year time period. Thus, 5% of the economic potential is adopted each year. Since the amount of technical and economic potential is reevaluated in each model year as economic conditions and steam output change, the annual additions will vary. However, over the 25-year projection horizon, if economic conditions remained constant and steam loads did not increase, the cumulative capacity additions would be equal to the total economic potential determined in the first model projection year

The analysis considers the annual cash flow from the investment to be equal to the value of the cogenerated electricity, less the cost of the incremental fuel required to generate it discounted using the 10-year Treasury bill rate as projected in the MAM plus a risk premium. For this purpose,

the annual cost of fuel (natural gas) and the value of the electricity are based on the prices in effect in the model year in which the evaluation is conducted. The model assumes that the electricity is valued at the average industrial electricity price in the region, net of standby charges that would be incurred after installing cogeneration. The standby charges were assumed to be some fraction of the industrial electricity rate (usually 10%).

For natural gas, the price of firm-contract natural gas was assumed to apply. Since a simplified representation is required for the broad modeling needs in the IDM, non-fuel operating costs are not included. The costs are small relative to fuel costs and can be difficult to quantify with aggregate, load segment methodology being used as well. The payback is determined by dividing the investment by the average annual cash flow.

Benchmarking

The IDM energy demand projections are benchmarked to historical data values presented in EIA's *Monthly Energy Review.*[13] The national-level values reported here were allocated to the census divisions using the 2017 *State Energy Data System* (SEDS).[14] The benchmark factors are based on the ratio of the SEDS value of consumption for each fuel to the consumption calculated by the model at the census region level. The SEDS covers historical data. After the last historical data year, the IDM results are benchmarked to the *Short-Term Energy Outlook* (STEO). The STEO benchmark is done at the national level and generally extends a few years past the last historical year. Past the STEO projection years, the IDM retains a composite of benchmark factors (SEDS and STEO) and applies these composite benchmark factors through the projection. The composite benchmark factors are viewed as a correction for under or over-coverage of energy consumption produced by the model. For example, the IDM may produce an estimate of total industrial consumption of coal that is 5% too low from the best EIA historical estimates of coal consumption in the industrial sector. Thus the industrial model is assumed to show a 5% under coverage of coal consumption. The benchmark factors adjust for this perceived under or over coverage and seek to insure that the IDM estimates are comparable to other International Energy Agency (IEA) fuel consumption estimates.

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[13] U.S. Energy Information Administration, *Monthly Energy Review, September 2013*, http://www.eia.gov/totalenergy/data/monthly/archive/00351309.pdf.

[14] U.S. Energy Information Administration, *State Energy Data System,* Consumption Data in Btu, 1960–2015, https://www.eia.gov/state/seds/sep_use/total/csv/use_all_btu.csv

Energy-intensive manufacturing industries

Food products (NAICS 311): End-use method

Figure 3. Food industry end uses
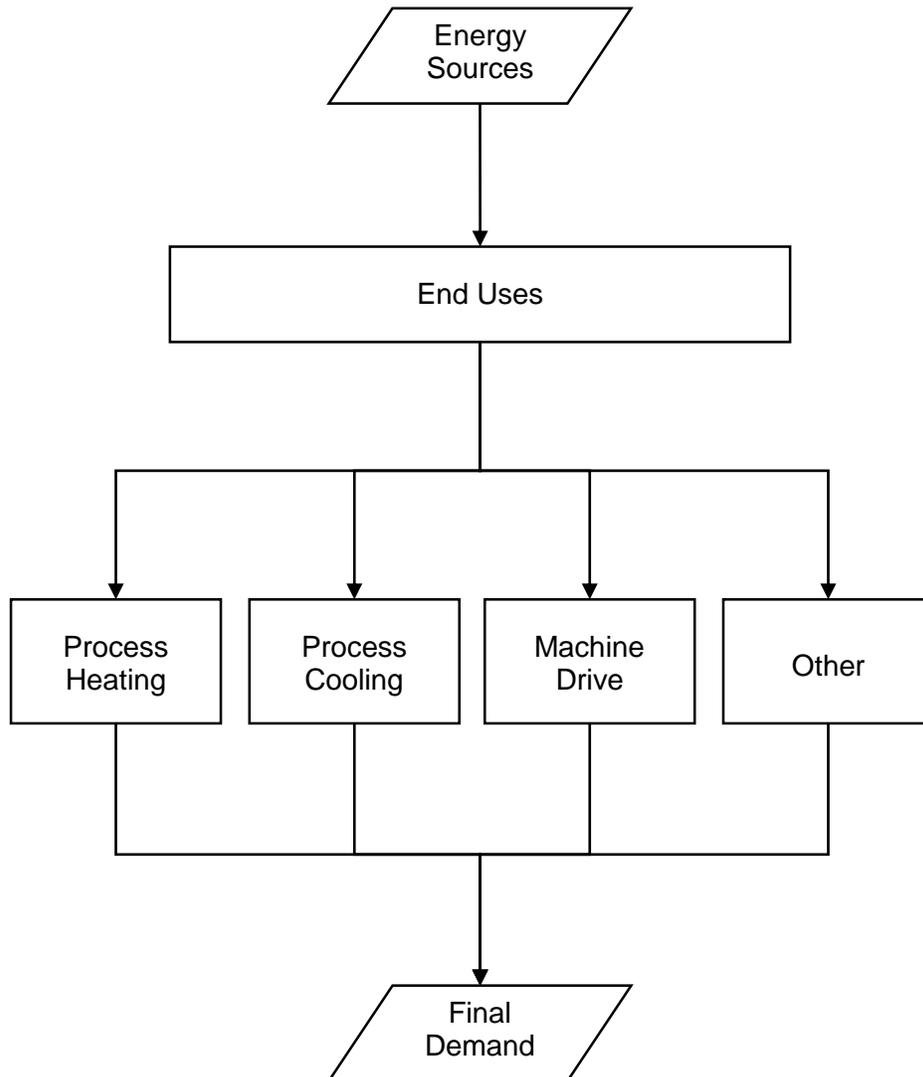
Source: U.S. Energy Information Administration

The food industry is modeled by the four subsector industries: Grain and Oilseed Milling (NAICS 3112); Dairy Product Manufacturing (NACIS 3115); Animal Slaughter and Processing and Seafood Product Preparation and Packaging (NAICS 3116, 3117); and Other Food Products. Energy use in the food products industries for the PA component was estimated for each of four major end-use categories of Process Heating, Process Cooling and Refrigeration, Machine Drive, and All Other Uses. Figure 3 portrays the PA component's end-use energy flow for the food products industry. A motor stock model, described on page 16, calculates electricity consumption for the machine drive end use.

Paper and allied products (NAICS 322): Process flowsheet method

Figure 4. Paper manufacturing industry process flow
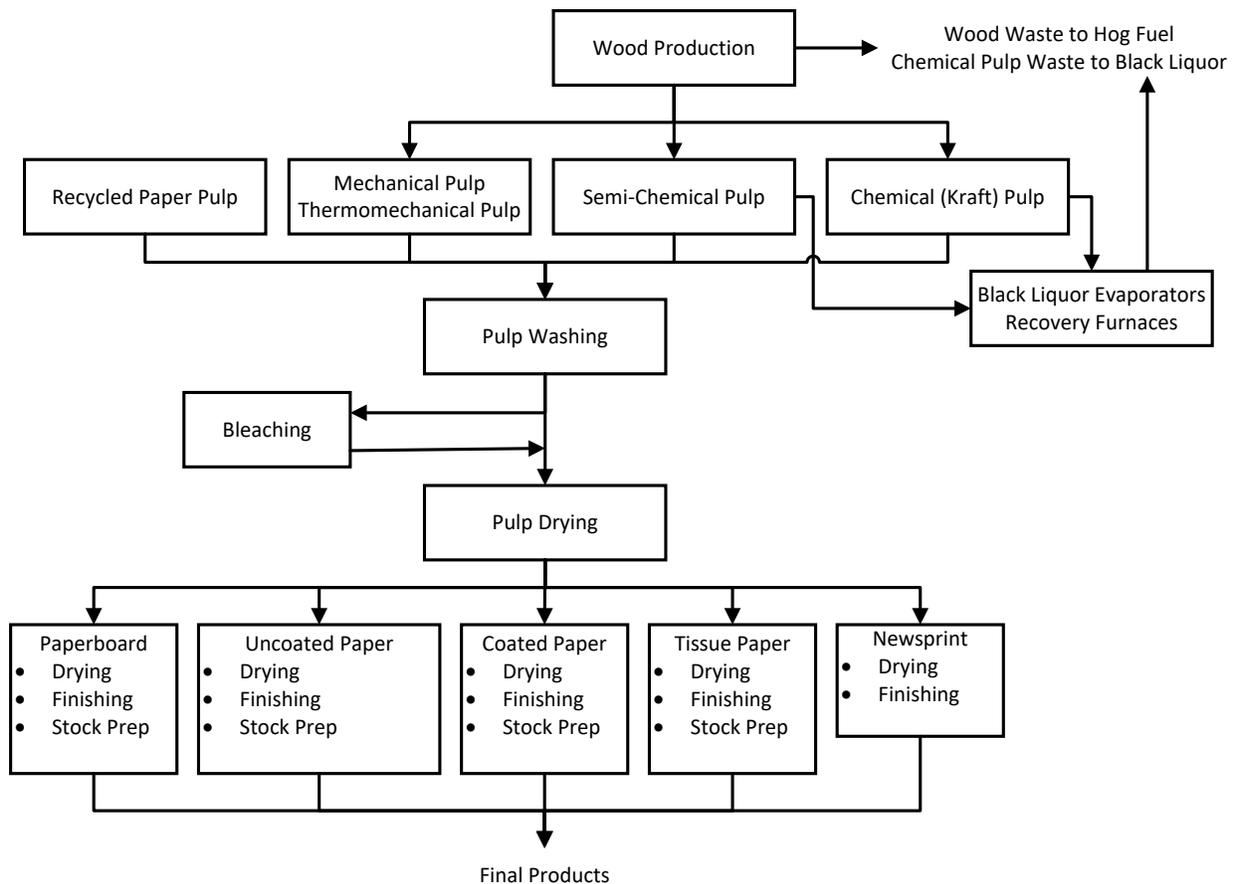
Source: U.S. Energy Information Administration

The paper and allied products industry's principal processes involve the conversion of wood fiber to pulp, and then of paper and board to consumer products that are generally targeted at the domestic marketplace. The industry produces a full line of paper and board products, as well as dried pulp, which is sold as a commodity product to domestic and international paper and board manufacturers.

Figure 4 illustrates the major process steps for all pulp and paper manufacturing that are process steps (denoted by isx) in the model. Almost all process steps have multiple technologies. The wood preparation step is removing the bark and chipping the whole tree into small pieces. Pulping is the process by which the fibrous cellulose in the wood is removed from the surrounding lignin. Pulping can be conducted with a chemical process (for example, Kraft, semi-chemical) or a mechanical process. The pulping step also includes processes such as drying, liquor evaporation, effluent treatment, and miscellaneous auxiliaries. Bleaching is required to produce white paper stock. The pulp and paper industry has significant recycling and the recycled paper pulp process. Black liquor that is used as fuel in combined heat and power (CHP) and boilers is produced from chemical process step outputs to black liquor evaporators and recovery furnaces. Wood preparation produces hog fuel that is also used as fuel in CHP and boilers.

Paper and paperboard-making takes the pulp from the preceding processes and makes the final paper and paperboard products. The manufacturing operations after pulp production are similar for all of the paper end products even though their processes differ. The processes in the papermaking step include converting/packaging, coating/re-drying, effluent treatment, and other miscellaneous processes associated with the process steps of drying, finishing, and stock prep.

The paper products are associated with the process steps of paperboard, uncoated paper, coated paper, tissue paper, and newsprint. The major paperboard products include Kraft paperboard, corrugating medium, and recycled paperboard. Future additions to pulping capacity are assumed to reflect a slight relative increase in waste pulping via increased use of market pulp. This assumption reflects recent trends in additional imports of market pulp.

Bulk chemical industry (parts of NAICS 325): End-use method

Figure 5. Bulk chemical end uses
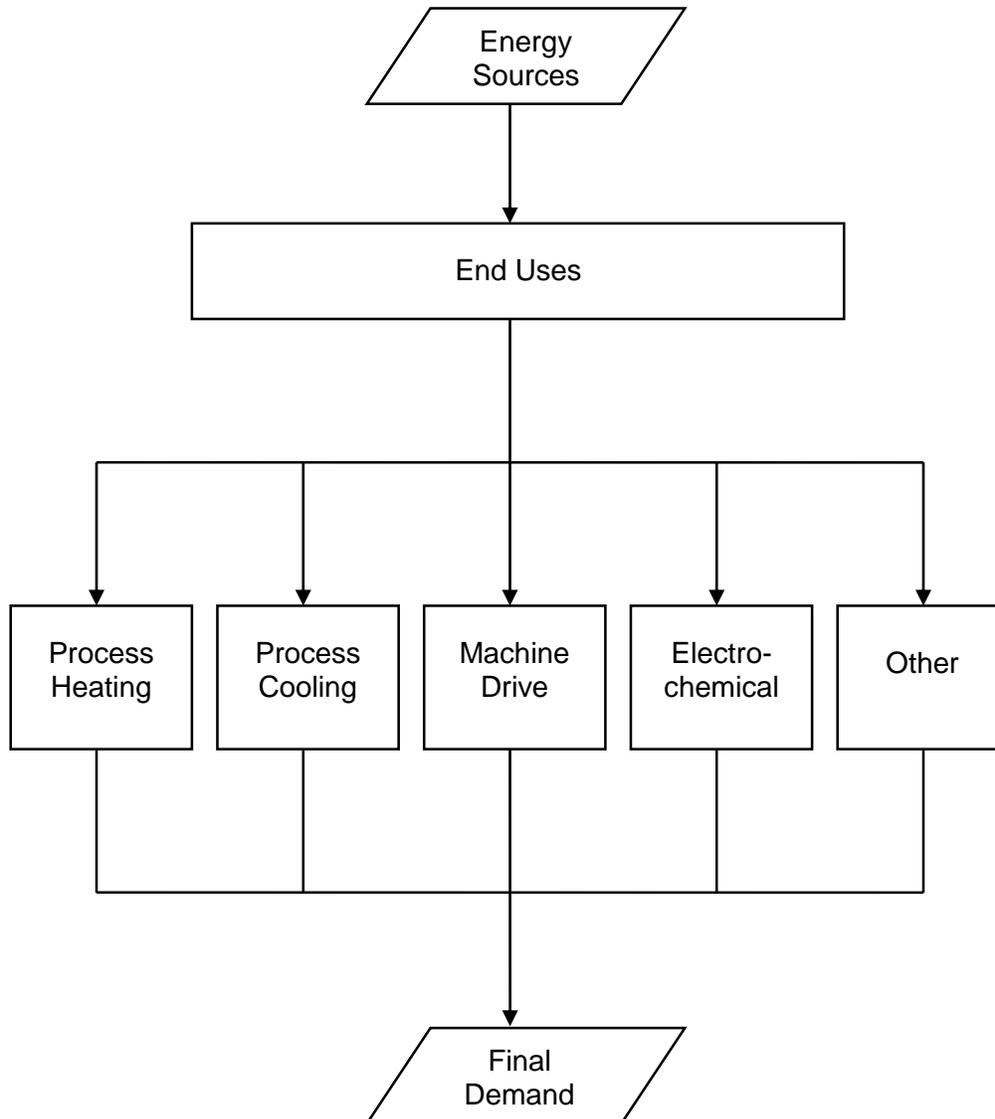
Source: U.S. Energy Information Administration

The bulk chemical sector is very complex. The modeled subsector industries are: inorganic chemicals; organic chemicals; Resins and Synthetics; and Agricultural Chemicals. Their NAICS codes are listed in Table 2. The chemical industries are aggregated to the bulk chemicals output while the other chemicals industries are part of the Balance of Manufacturing. This industry is a major energy feedstock user and a major producer of combined heat and power.

Table 4. Chemical products in the bulk chemical industry model

Organic chemicals	Inorganic chemicals	Resins	Agricultural chemicals
Ethylene	Acetylene	Polyvinyl chloride	Ammonia
Propylene	Chlorine	Polyethylene	Phosphoric acid
Butadiene	Oxygen	Polystyrene	Other agricultural chemicals
Acetic acid	Sulfuric acid	Styrene-butadiene	
Acrylonitrile	Hydrogen	Rubber	
Ethylbenzene	Other inorganic chemicals	Vinyl chloride	
Ethylene dichloride		Other resins	
Ethylene glycol			
Ethylene oxide			
Formaldehyde			
Methanol			
Styrene			
Vinyl acetate			
Ethanol			
On-purpose propylene (and byproduct ethylene)			
Other organic chemicals			

Source: Industrial Demand Module

The bulk chemical industry's energy consumption patterns are equally complex, with demands for heat, steam, electricity, and energy feedstocks driven by the demand for production of numerous chemical products, as well as the processes and technologies involved in making these products. Because of this complexity, only ethanol and hydrogen production are singled out for the tracking of specific energy consumption as these chemicals are incorporated directly into the supply modules of NEMS. The rest of the chemicals are aggregated into the four categories as defined in Table 2. There are 15 organic, 5 inorganic, 5 resins, and 2 agricultural chemicals. Modeling of energy consumption within these groups is accomplished by the TPC method used for most other industries as described in Figure 4. A limited feedstock selection algorithm is included as well (see below).

The delineation of feedstock demand applies only to the PA component of the bulk chemical energy consumption projections. The PA component also estimates energy consumption for direct process heating, cooling and refrigeration, machine drive, electro-chemical processes, and other uses. The BSC and BLD components remain the same for this industry as in other models. Thus, steam demand projections are passed from the PA component to the BSC component. The BSC component then calculates fuel consumption to generate the steam. Also, as in the other modules, the BLD component projects energy consumption for this industry's use of its facilities for space heating, space cooling, and lighting.

The feedstock UECs are initialized from the 2014 MECS data the same way as the fuel components, but unlike most fuels, the feedstock TPC rates of change are set to zero. In other words, the UECs for feedstocks are assumed not to improve over time. This assumption is based on the inherent

stoichiometric relationship between basic chemical products, such as ethylene, propylene, and ammonia, and their feedstocks such as natural gas, NGL, and naphtha.

To a large degree, the NGL and naphtha petrochemical feedstocks can substitute for one another, especially for the production of commodity chemicals like ethylene, propylene, and butadiene. Base year liquid feedstock total has been divided up into the two groups using 2014 MECS data. Over time, as petrochemical shipments grow in the projections, the model splits up incremental petrochemical feedstock demand needed to satisfy growing chemical shipments between NGL and naphtha based upon the relative pricing of the two; that is, the cheaper NGL is relative to naphtha, the more NGL will dominate in its share of total incremental feedstock demand.

In AEO2014, NGL components (ethane, propane, normal butane, isobutane, and pentanes plus/natural gasoline) were segregated. After making the economic decision between feedstock demand shares of NGL vs. naphtha, the NGL demand was filled by the NGL components. All ethane (production plus net imports) was assumed to be consumed in the industrial model. The rest is filled by the other NGL, proportional to their respective historical feedstock use.

Finally, there is an option to use refinery-produced propylene to fulfill some of the incremental organic shipments demand growth. Propylene price is based on production cost from the Liquid Fuels Market Model (LFMM), and this price is competed against feedstock costs (NGL and naphtha).

In the United States, the production of ammonia and hydrogen primarily uses natural gas as the feedstock. Nevertheless, there has been some interest in using other feedstocks, such as coal and biomass, for both ammonia and hydrogen, as well as electrolytic process for hydrogen. EIA has performed research analyses on the relative cost-effectiveness of these alternative feedstocks. Cost-effectiveness evaluations for these alternatives were performed for ammonia and hydrogen. The benefits and costs of replacing existing natural gas plants were estimated and compared in the pro forma analysis. The competition between natural gas and the alternatives for a new plant was also analyzed. The costs of using the alternatives were found to be significantly prohibitive, and continue to be in light of continued relatively inexpensive natural gas due to increasing domestic supply. This issue continues to be studied by EIA and will be updated in future projections as appropriate.

Glass and glass products industry (NAICS 3272, 32799): Process flowsheet method

Figure 6. Glass industry process flow
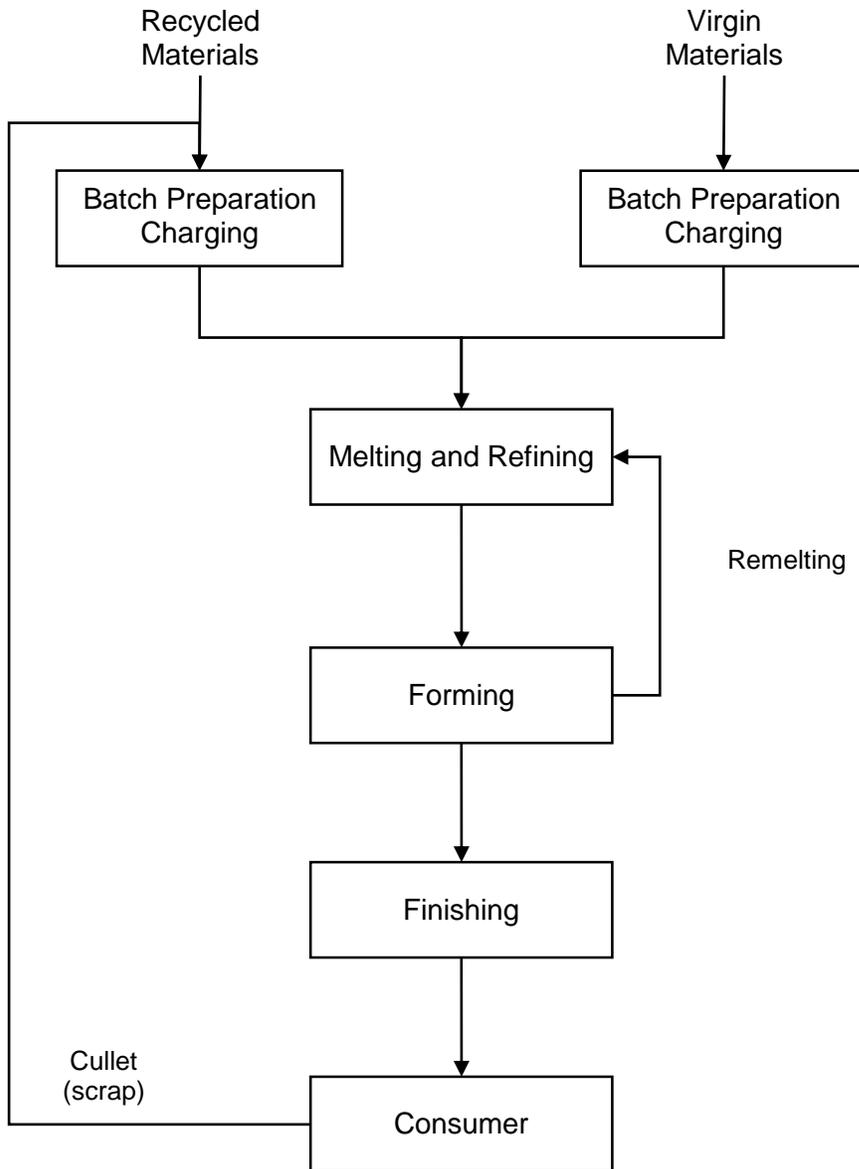
Source: U.S. Energy Information Administration

An energy use profile has been developed for the whole glass and glass products industry, NAICS 3272. This industry definition includes glass products made from purchased glass. The glass-making process contains four process steps: batch preparation, melting and refining, forming, and finishing. Figure 6 provides an overview of the process steps involved in the glass and glass products industry. Although

cullet (scrap) and virgin materials are shown separately to account for the different energy requirements for cullet and virgin material melting, glass makers generally mix cullet with the virgin material.

The fuels consumed are predominantly for direct fuel use because there is very little steam demand. Direct fuel use is mainly in furnaces for melting.

Cement and lime industries (NAICS 32731, 32741): Process flowsheet method

Figure 7. Cement industry process flow
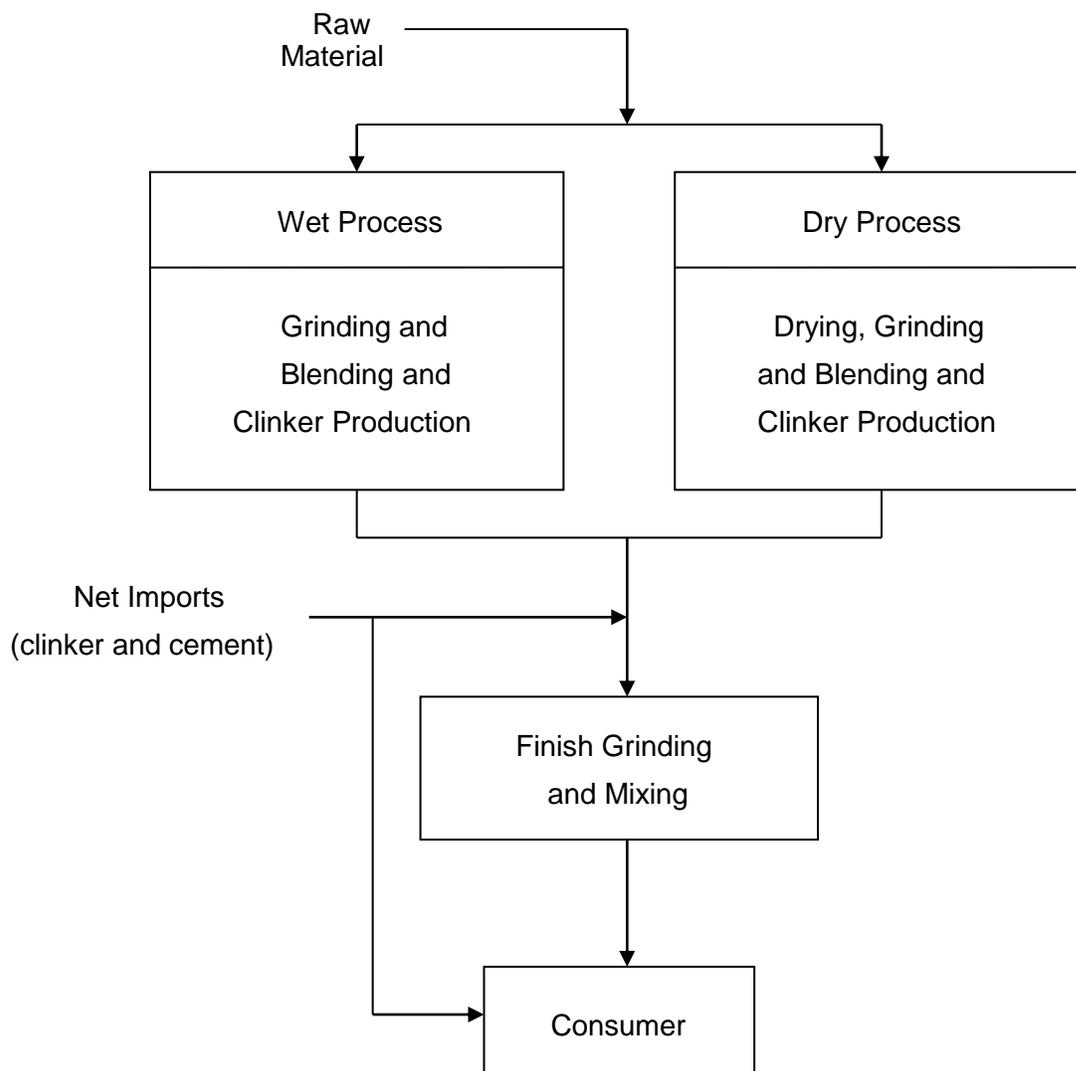
Source: U.S. Energy Information Administration

The cement (NAICS 32731) and lime (NAICS 32741) industries' energy consumption are reported together in NEMS. Both cement and lime are represented using a process flow model that derives energy use from specific technologies, rather than engineering judgment of general energy use.

The cement industry uses raw materials from non-manufacturing quarrying and mining industries. These materials are sent through crushing and grinding mills and converted to clinker in the clinker-producing step. This clinker is then further ground to produce cement. The industry produces cement by two major processes: the wet process and the dry process. The dry process is less energy-intensive than the wet process, and thus the dry process has steadily gained favor in cement production. As a result, it is assumed in the model that all new plants will be based on the dry process. Figure 7 provides an overview of the process steps involved in the cement industry.

Since cement is the primary binding ingredient in concrete mixtures, it is used in virtually all types of construction. As a result, the U.S. demand for cement is highly sensitive to the level of construction activity, which is projected for NEMS using the MAM and transferred to the IDM as an input.

Lime is used in a number of ways. The majority of lime is used in metallurgical applications, primarily iron and steel, and flue gas desulfurization. Other major uses are water treatment, construction, including cement, and pulp and paper. Lime is used chemically to make the properties of a product more desirable, such as lowering acidity; as part of a chemical reaction, as in cement; and to remove impurities, such as in metallurgical applications or flue gas desulfurization.

Figure 8. Lime process flow

```
┌──────────┐
│  Raw     │───────────────┐
│ Material │               │
└──────────┘               ▼
              ┌────────────────────────┐
              │    Primary Crushing     │
              └────────────────────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │   Secondary Crushing    │
              └────────────────────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │      Kiln Heating       │
              └────────────────────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │        Cooling          │
              └────────────────────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │  Screening and Milling  │
              └────────────────────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │       Consumer          │
              └────────────────────────┘
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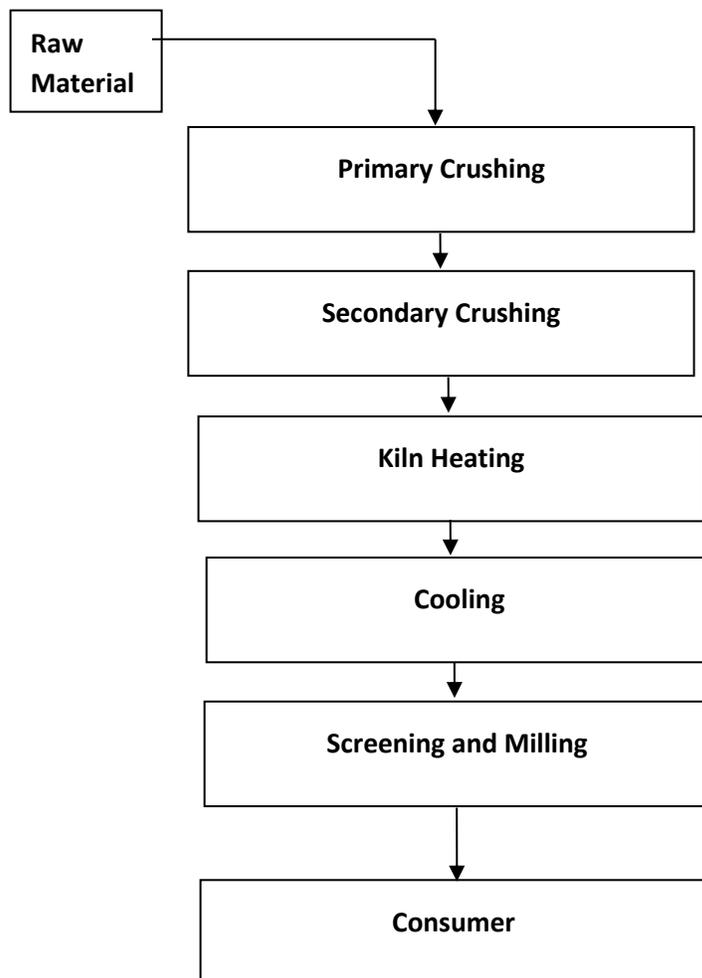
Source: U.S. Energy Information Administration

Iron and steel Industry: (NAICS 3311, 3312, 324199): process flowsheet method

Figure 9. Iron and steel industry process flow

Final Products
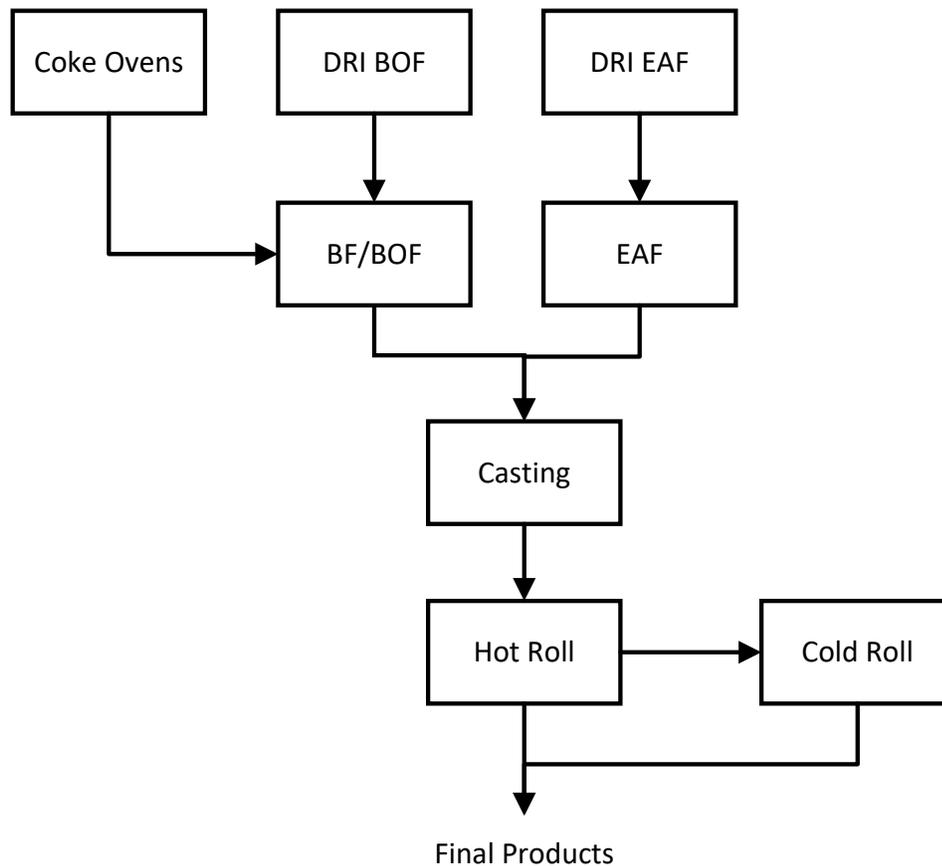
Source: U.S. Energy Information Administration

Figure 9 shows the iron and steel industry major process steps. Almost all process steps have multiple technologies that are addressed in the detailed iron and steel documentation. The process steps are: Coke making, Iron making in Direct Reduced Iron for Basic Oxygen Furnaces (DRI BOF), Direct Reduced Iron for Electric Arc Furnaces (DRI EAF), Blast Furnace/Basix Oxygen Furnace (BF/BOF); Steel making in BF/BOF and EAF, and steel product making in casting, hot roll, and cold roll. An agglomeration step is excluded from the IDM iron and steel submodule because it is considered part of mining. Iron ore and coal are the basic raw materials that are used to produce iron.

Steel manufacturing plants can be classified as integrated or non-integrated. The classification is dependent upon the number of the major process steps that are performed in the facility. Integrated plants perform all the process steps, whereas non-integrated plants, in general, perform only the last three steps.

Iron is produced in the blast furnace (BF), which is then charged into a basic oxygen furnace (BOF) to produce raw steel. Coke ovens and blast furnaces also produce a significant amount of byproduct fuels,

which are used throughout the steel plant. The direct reduced iron (DRI) related to BOF and EAF also produces iron. The electric arc furnace (EAF) is used to produce raw steel from an all-scrap (recycled materials) and sometimes supplemented with direct reduced iron or hot briquetted iron.

The raw steel is cast into blooms, billets, or slabs using continuous casting. Some cast steel is sold directly (for example, forging-grade billets). The majority is further processed by Hot Roll into various mill products. Some of these are sold as hot rolled mill products, while others are further processed by Cold Roll to impart surface finish or other desirable properties.

Alumina and aluminum industry (NAICS 3313): Process flowsheet method

The U.S. aluminum industry consists of two major sectors: the primary aluminum sector, which uses alumina as raw material, and the secondary sector, which uses collected aluminum scrap as a raw material. The primary and secondary aluminum industries have historically catered to different markets, but these distinctions are fading. Traditionally, the primary industry bought little scrap and supplied wrought products, including sheet, plate, and foil. The secondary industry is scrap-based and has historically supplied foundries that produce die, permanent mold, and sand castings. More recently, secondary aluminum smelters have started supplying wrought (sheet) stock. In addition, in the past decade, the primary producers have been moving aggressively into recycling aluminum, especially used beverage cans.

Figure 10 provides an overview of the process steps involved in the aluminum industry. The energy use analysis accounts for energy used in NAICS 3313 which includes the following:

- o Alumina Refining (NAICS 331311)
- o Primary Aluminum Production (NAICS 331312)
- o Secondary Smelting and Alloying of Aluminum (NAICS 331314)
- o Aluminum Sheet, Plate, Foil Manufacturing (NAICS 331315)
- o Aluminum Semi-fabrication of Products such as Extrusions, Tube, Cable, and Wire (found in NAICS 3316 and NAICS 331319)

Note: aluminum foundry castings (die-casting/permanent mold/other) are not considered as part of NAICS 331311.

Figure 10. Aluminum industry process flow
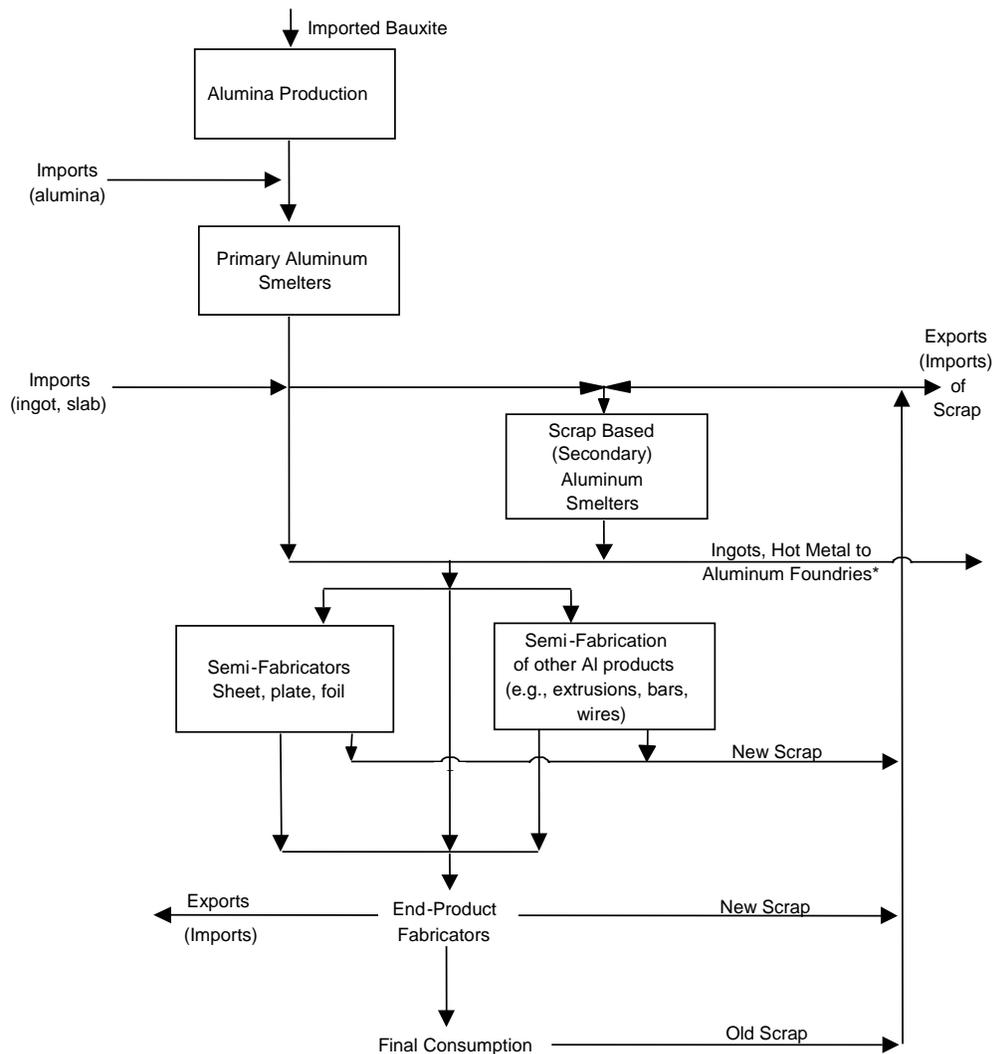
Source: U.S. Energy Information Administration

Non-energy-intensive manufacturing industries

Metal-based durables industry group (NAICS 332-336): End-use method

The metal-based durables industry group consists of industries that manufacture fabricated metals; machinery; computer and electronic products; transportation equipment; and electrical equipment, appliances, and components. Typical processes found in this group include re-melting operations followed by casting or molding, shaping, heat-treating processes, coating, and joining and assembly.

Given this diversity of processes, the industry group's energy is represented using the end-use method based on the 2014 MECS.[15] End-use processes for metal-based durables are the same as in bulk chemicals, as shown in Figure 5. A motor stock model, described on page 16, calculates electricity consumption for the machine drive end use.

Other non-energy-intensive manufacturing industries: End-use method

This category is a group of miscellaneous industries consisting of wood products (NAICS 321) and plastic and rubber products (NAICS 326). The balance of manufacturing category includes beverage and tobacco products (NAICS 312), textile mills (NAICS 313), textile product mills (NAICS 314), apparel (NAICS 315), leather and allied products (NAICS 316), printing and related support (NAICS 323), furniture and related products (NAICS 327), and miscellaneous manufacturing (NAICS 339). In addition, balance of manufacturing includes other industries that are not represented in specific models, such as industries manufacturing other chemicals (NAICS 325), other petroleum and coal products (NAICS 324), other non-metallic mineral product manufacturing (NAICS 327), and other primary metals (NAICS 331). Data limitations and the lack of a dominant energy user limit disaggregation of these industries. Wood products manufacturing is of interest because the industry derives a majority of its energy from biomass in the form of wood waste and residue. The plastics manufacturing industry produces goods by processing goods from plastic materials but does not produce the plastic. A motor stock model, described on page 16, calculates electricity consumption for the machine drive end use for balance of manufacturing.

Non-manufacturing industries

The non-manufacturing industries do not have MECS as the predominant source for energy consumption data as the manufacturing industries do. Instead, UECs for the agriculture, mining, and construction industries are derived from various sources collected by a number of federal agencies, notably U.S. Department of Agriculture (USDA) and the U.S. Census Bureau, part of the U.S. Department of Commerce. Furthermore, unlike the majority of manufacturing industries, the TPCs for non-manufacturing are not fixed; they change over time. This dynamic process depends on output from other NEMS modules such as the Commercial Demand Module (CDM) and the Transportation Demand Module (TDM), which are used in the agriculture, construction, and mining models. For mine productivity, the Oil and Gas Supply Module (OGSM) provides consumption data for oil and natural gas wells, and the Coal Market Module (CMM) provides data for coal mines.

Energy consumption data for the two agriculture sectors (crops and other agriculture) are largely based on information contained in the Census of Agriculture conducted by the National Agricultural Statistical Service of the U.S. Department of Agriculture,[16, 17] (USDA-NASS) and a special tabulation from the USDA-

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[15] U.S. Energy Information Administration (EIA), *2014 Manufacturing Energy Consumption Survey*, http://www.eia.gov/consumption/manufacturing/index.cfm, March 2013.

[16] U.S. Department of Agriculture, National Agricultural Statistical Service, *2007 Census of Agriculture*, February 2009 http://www.agcensus.usda.gov/Publications/2007/index.asp.

[17] U.S. Department of Agriculture, National Agricultural Statistical Service, *2012 Census of Agriculture*, February 2014 https://www.agcensus.usda.gov/Publications/2012/.

NASS.[18] Expenditures for four energy sources were collected for crop farms and livestock farms. These data were converted from dollar expenditures to energy quantities using prices from USDA and EIA.

Sources used are EIA's Fuel Oil and Kerosene Sales (FOKS)[19] for distillate consumption, Agricultural Resource Management Survey (ARMS),[20] and the U.S. Census Bureau's Census of Mining[21, 22] and Census of Construction.[23, 24] Also, the use of HGL, often referred to as liquefied petroleum gas (LPG), is now accounted for in the agriculture and especially the construction industries. Non-manufacturing consumption is no longer dictated solely by the SEDS to MECS difference as it has been in previous years. The mining industry is divided into three sectors in the IDM: coal mining, oil and natural gas extraction, and other mining. The quantities of 7 energy types consumed by 29 mining sectors were collected as part of the 2012 Economic Census of Mining by the U.S. Census Bureau.[25] The data for the 29 sectors were aggregated into the 3 sectors included in the IDM, and the physical quantities were converted to Btu for use in NEMS.

Only one construction sector is included in the IDM. Detailed statistics for the 31 construction subsectors included in the 2012 Economic Census were aggregated. Expenditure amounts for five energy sources were collected by the U.S. Census Bureau.[26] These expenditures were converted from dollars to energy quantities using EIA price data.

These sources are considered to be the most complete and consistent data available for each of the three non-manufacturing sectors. These data, supplemented by available EIA data, are used to derive total energy consumption for the non-manufacturing industrial sectors. The additional EIA data are from the *State Energy Data System 2013*.[27] The source data relate to total energy consumption and provide no information on the processes or end uses for which the energy is consumed. Therefore, the UECs for the mining and construction industries relate energy consumption for each fuel type to value of

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[18] Jim Duffield, USDA-NASS, *2012 Census of Agriculture Special Tabulation*, June 2017, https://www.nass.usda.gov/Data_and_Statistics/Special_Tabulations/Completed_Tabulations/data-lab-records.php.

[19] U.S. Energy Information Administration, Fuel Oil and Kerosene Survey 2014 (FOKS), (Washington, DC, December 2015), https://www.eia.gov/petroleum/fueloilkerosene/archive/2014/foks_2014.php.

[20] Agriculture Research Management Survey (ARMS), United States Dept. of Agriculture, Economic Research Service, 2014, (Washington DC, December 1, 2015; revised May 2, 2016) http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices.aspx#.UxcWZ_ldWCm.

[21] U.S. Census Bureau, 2007 Economic Census, Mining Industry Series, (Washington, DC, 2009), https://www.census.gov/data/tables/2007/econ/census/mining-reports.html.

[22] U.S. Census Bureau, 2012 Economic Census, Mining Industry Series, (Washington, DC, 2015), https://www.census.gov/data/datasets/2012/econ/census/2012-mining.html.

[23] U.S. Census Bureau, 2007 Economic Census, Construction Summary Series, (Washington, DC, 2009), https://www.census.gov/data/tables/2007/econ/census/construction.html.

[24] U.S. Census Bureau, 2012 Economic Census, Construction Summary Series, (Washington, DC, 2015), https://data.census.gov/cedsci/table?q=EC1223SG01&g=0100000US,.04000.001_0200000US1,2,3,4&tid=ECNBASIC2012.EC1223SG01&hidePreview=false.

[25] U.S. Census Bureau, 2012 Economic Census, Mining Industry Series, (Washington, DC, 2015), https://www.census.gov/data/datasets/2012/econ/census/2012-mining.html.

[26] U.S. Census Bureau, 2012 Economic Census, Construction Summary Series, (Washington, DC, 2015), https://data.census.gov/cedsci/table?q=EC1223SG01&g=0100000US,.04000.001_0200000US1,2,3,4&tid=ECNBASIC2012.EC1223SG01&hidePreview=false.

[27] U.S. Energy Information Administration, *State Energy Data System 2013* (Washington, DC, June 2013).

shipments. For the two agricultural industries in the IDM, a submodule was implemented and is described below.

Agricultural submodule

U.S. agriculture consists of three major sub-sectors: crop production, which is dependent primarily on regional environments and crops demanded; animal production, which is largely dependent on food demands and feed accessibility; and all remaining agricultural activities, primarily forestry and logging. The energy use analysis accounts for energy used in the following categories, with the second and third category combined for modeling purposes:

- o Crop Production and Support Activities (NAICS 111 & 1151)
- o Animal Production and Support Activities (NAICS 112 & 1152)
- o Forestry and Logging and Support Activities (NAICS 113 & 1153)

Consumption in these industries is tied to specialized equipment, which often determines the fuel requirement with little flexibility. Within each of these sub-industries, the key energy-using equipment can be broken into three major categories: off-road vehicles; buildings; and other equipment, which is primarily irrigation equipment for crop production.[28] In the IDM, building energy consumption is driven by building characteristics retrieved from the NEMS Commercial Demand Module. Vehicle energy consumption is determined by vehicle efficiencies, which are retrieved from the NEMS Transportation Demand Module.

Mining submodule

The mining sector comprises three subsectors: coal mining, metal and nonmetal mining, and oil and natural gas extraction. Energy use is based on what equipment is used at the mine and onsite vehicles used. All mines use extraction equipment and lighting, but only coal and metal and nonmetal mines use grinding and ventilation. Characteristic of the non-manufacturing sector, TPCs are influenced by efficiency changes in buildings and transportation equipment.

Coal mining production is obtained from the NEMS CMM. Currently, approximately 70% of the coal is assumed to be mined at the surface, while the rest is mined underground. As these shares evolve, however, so does the energy consumed because surface mines use less energy overall than underground mining. Moreover, the energy consumed for coal mining depends on coal mine productivity, which is also obtained from the CMM. Distillate fuel and electricity are the predominant fuels used in coal mining. Electricity used for coal grinding is calculated using the raw grinding process step from the cement industry submodule described beginning on page 102. In metal and non-metal mining, energy use is similar to coal mining. Output used for metal and non-metal mining is derived from the Macroeconomic Analysis Module's variable for *other* mining, which also provides the shares of each.

For oil and natural gas extraction, production is derived from the OGSM. Energy use depends on the fuel extracted as well as whether the well is conventional or unconventional, for example, extraction from tight and shale formations, percentage of dry wells, and well depth.

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[28] Eugeni, Edward, SRA International "Report on the Analysis and Modeling Approach to Characterize and Estimate Fuel Use by End-Use Applications in the Agriculture and Construction Industries," unpublished report prepared for the Office of Energy Analysis (Washington, DC: March 2011).

Construction submodule

Construction uses off-road distillate, asphalt and road oil, as well as electricity, natural gas, and HGLs. Asphalt and road oil are tied to state and local government real investment in highways and streets, and this investment is derived from the MAM. TPCs for distillate are directly tied to the Transportation Demand Module's heavy- and medium-duty vehicle efficiency projections. For non-vehicular construction equipment, TPCs are a weighted average of vehicular TPCs and highway investment.

Additional model assumptions

Legislative and regulatory requirements

The Energy Policy Act of 1992 (EPACT92) and the Clean Air Act Amendments of 1990 (CAAA) contain requirements that are represented in the IDM. These requirements fall into three main categories: coke oven standards; efficiency standards for boilers, furnaces, and electric motors; and industrial process technologies. The IDM assumes the leakage standards for coke oven doors do not reduce the efficiency of producing coke or increase unit energy consumption. The IDM uses heat rates of 1.25 (80% efficiency) and 1.22 (82% efficiency) for gas and oil burners, respectively. These efficiencies meet the EPACT92 standards. The EPACT92 electric motor standards set minimum efficiency levels for all motors up to 200 horsepower purchased after 2002. The EISA2007 increases the motor efficiency standard for all motors up to 500 horsepower purchased after 2011. All motors represented in the motor stock model are at least as efficient as the standards for a given projection year. The IDM incorporates the necessary reductions in unit energy consumption for the energy-intensive industries.

Section 108 of the Energy Policy Act of 2005 (EPACT05) requires that federally funded projects involving cement or concrete increase the amount of recovered mineral component (for example, fly ash or blast furnace slag) used in the cement. Such use of mineral components is a standard industry practice, and increasing the amount could reduce both the quantity of energy used for cement clinker production and the level of process-related carbon dioxide (CO_2) emissions. Because the proportion of mineral component is not specified in the legislation, possible effects of this provision are not currently simulated in the model. When specific regulations are promulgated, their estimated impact may be modeled in NEMS. However, the current cement industry model does include the capability to increase the amount of blended component in the clinker mix. Section 1321 of EPACT05 extends the Section 29 Production Tax Credit (PTC) for non-conventional fuels to facilities producing coke or coke gas. The credit is available for plants placed in service before 1993 and between 1998 and 2010. Each plant can claim the credit for four years. However, the total credit is limited to an annual average of 4,000 barrels of oil equivalent (BOE) per day. The value of the credit is currently $3.00 per BOE and will be adjusted for inflation in the future. Because the bulk of the credits will go to plants already operating or under construction, there is likely to be little impact on coke plant capacity.

The AEO2015 and AEO2016 motor model was adjusted based on regulations related to improving motor energy efficiency.[29, 30] The adjustments were to the related Input data in the file Indmotor.xml to reflect changes in motor energy efficiency.

Maximum Achievable Control Technology for Industrial Boilers (Boiler MACT): Section 112 of the Clean Air Act (CAA) requires the regulation of air toxics through implementation of the National Standards for Hazardous Air Pollutants (NESHAP) for industrial, commercial, and institutional boilers. The final regulations, known as Boiler MACT, are modeled starting in the AEO2014. Pollutants covered by Boiler MACT include the hazardous air pollutants (HAP), hydrogen chloride (HCl), mercury (Hg), dioxin/furan, carbon monoxide (CO), and particulate matter (PM). Generally, industries comply with the Boiler MACT regulations by including regular maintenance and tune-ups for smaller facilities and emission limits and performance tests for larger facilities. Boiler MACT is modeled as an upgrade cost in the MAM. These upgrade costs are classified as *nonproductive costs*, which are not associated with efficiency improvements. The effect of these costs in the MAM is a reduction in shipments coming into the IDM.

California Assembly Bill 32: Emissions cap-and-trade as part of the Global Warming Solutions Act of 2006 (AB32) established a comprehensive, multi-year program to reduce greenhouse gas (GHG) emissions in California, including a cap-and-trade program. In addition to the cap-and-trade program, AB32 also authorizes the Low Carbon Fuel Standard (LCFS); energy efficiency goals and programs in transportation, buildings, and industry; combined heat and power goals; and renewable portfolio standards. Starting in AEO2014, the cap-and-trade provisions were modeled for industrial facilities, refineries, and fuel providers. GHG emissions include both non-CO2 and specific non-CO2 GHG emissions. The allowance price, representing the incremental cost of complying with AB32 cap-and-trade, is modeled in the NEMS Electricity Market Module via a region-specific emissions constraint. This allowance price, when added to market fuel prices, results in higher effective fuel prices in the demand sectors. Limited banking and borrowing, as well as a price containment reserve and offsets, have been modeled in the NEMS. AB32 is not modeled explicitly in the IDM, but enters the module implicitly through higher effective fuel prices and macroeconomic effects of higher prices, all of which affect energy demand and emissions.

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[29] U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE), 10 CFC Parts 429 and 431, Docket Number EERE-2011-BT-STD-0031, "Energy Conservation Program: Energy Conservation Standards for Pumps."

[30] Federal Register, 10 CFR Part 431, "Energy Conservation Program: Energy Conservation Standards for Commercial and Industrial Electric Motors," Department of Energy, Energy Efficiency and Renewable Energy (EERE). Vol. 79, No. 103, May 29, 2014.

4. Model Structure

First year: Initialize data and arrays

The first year of the projection cycle is used to set up arrays and initialize data used for projecting energy consumption. For the *2020 Annual Energy Outlook* (AEO2020), the first year of the cycle is 2014, which corresponds to the *2014 Manufacturing Energy Consumption Survey* (MECS). Although the model produces estimates of energy consumption for 2014, the true model does not start until 2015, which is mainly because of the industries that are modelled using a process flow process. The model will produce energy consumption estimates for the end-use industries, but the process-flow industries only use the first year to set up the arrays. The process-flow models write to the same data arrays set up during the base year but do a lot more *behind the scenes* calculations. These procedures are used to initialize the Industrial Demand Module (IDM):

Read model inputs include the following:

- Read INDRUN.TXT which contains special run parameters. For example it is used to turn calibration to State Energy Data System (SEDS)/Short-Term Energy Outlook (STEO) on and off.

- Read ITLBSHR.TXT building energy consumption for base year.

- Read cogeneration data files (called from IND).

- MecsLess860: Calculate 2014 boiler fuel by subtracting Form 923 cogeneration fuel from 2014 MECS indirect fuels.

- Read CHP fuel consumption data.

- Read mining input data.

- Read PRODFLOW.TXT containing process and assembly step definitions and flow rates from most recent MECS data (2014). Define structure of prodflow arrays.

- Read ITECH.TXT file with MECS-based UEC rates and the TPC assumptions.

- Read *Short-Term Energy Outlook* (INDSTEO.TXT) benchmark file with last available history data and national projections for the STEO projection years.

- Read exogenous macroeconomic data, shipments and employment, and energy price variables from NEMS system.

- Read ENPROD.TXT.

    o   Open output files for writing.

Industry processing

The industrial module processes by industry group and region. There are 21 industry groups, including 6 non-manufacturing, 7 energy-intensive, and 8 non-energy-intensive manufacturing industries. Within each industry, projections are calculated for each of four census regions and summed to create a U.S.-level estimate for each industry. Below is a list of subroutines used in the IDM.

    o   RDBIN: Read memory management file with previous years' data for this industry and region. This is used to create lag variables.

    o   REXOG: Assign exogenous macroeconomic and energy price variables that come from NEMS global variables.

    o   CALBTOT: Compute consumption of energy in the buildings component for those industries that have a buildings energy component.

    o   CALCSC: Evaluate changes in UECs based on technological possibility curves (TPC) for end-use industries only. For nonmanufacturing industries evaluate the TPC based on external data.

    o   AGTPC: Evaluate Technological Possibility Curves for agriculture industries only to replace standard TPC values.

    o   COALTPC: Evaluate TPCs for coal mining only.

    o   OGSMTPC: evaluate TPCs for oil and natural gas mining only.

    o   OTH_MINTPC: evaluate TPCs for other mining only.

    o   CONTPC: evaluate TPCs for construction only.

    o   CALPROD: Compute revised productive capacity and throughput by process and assembly step and vintage; implement retirement and vintage assumptions for end-use industries.

    o   CALPATOT: Compute consumption of energy in the process assembly component for end-use industries.

    o   CALBYPROD: Calculate consumption of byproduct fuels.

    o   MOTORS: Compute consumption of electricity for machine-drive for end-use industries only

    o   CALGEN: Compute onsite electricity generation for sale and internal use by fuel for all industries except iron and steel and pulp and paper. Calculates steam for cogeneration and estimates penetration of new builds. Calls the following routines:

    o   COGENT: Read cogeneration assumptions spreadsheet (first year).

    o   SteamSeg: Assign fraction of steam load in current load segment for current industry.

    o   COGINIT: Initialize the cogeneration data arrays with capacity, generation, and fuel-use data

Process flow industry submodules

    o   CEMENT_INDUSTRY submodule, which obtains exogenous inputs from the READ_CEMENT subroutine used by cement and aluminum submodules.

- o   LIME_INDUSTRY submodule.
- o   ALUMINUM_INDUSTRY submodule, which obtains exogenous inputs from the READ_CEMENT subroutine.
- o   GLASS_INDUSTRY submodule, which obtains exogenous inputs from the READ_CEMENT subroutine.
- o   IRONSTEEL_INDUSTRY submodule, which obtains exogenous inputs from the IS_GETDATA subroutine.
- o   PAPERPULP_INDUSTRY submodule, which obtains exogenous inputs from the IS_GETDATA subroutine.

National summaries

- o   NATTOTAL: Accumulate total energy consumption over all industries.
- o   CONTAB: Accumulate aggregates for non-manufacturing heat and power.

Apply exogenous adjustments and assign values to global variables

- o   WEXOG
- o   SEDS Benchmarking: SEDS years (through 2013): calculate regional benchmark factors as the ratio of actual consumption to model consumption for each fuel in four census regions.

Post SEDS Years (2014-on): optionally, multiply model consumption by the SEDS benchmark factors:

- o   Disaggregate energy consumption from four census regions to nine census divisions using shares from SEDS.
- o   Calibrate regional energy consumption to match the latest year of national-level history data (from the STEO file).
- o   STEO Benchmarking.

STEO years: calculate national benchmark factors as the ratio of model consumption for each fuel to the STEO projection for each fuel.

Post-STEO years: optionally, over the period 2013 to 2014, multiply model consumption by the STEO benchmark factors.

- o   Assign final results to NEMS variables.

Main subroutines and equations

This section provides the solution algorithms for the IDM. The subroutines that are only associated with the process flow models are documented in the sections for cement and lime, aluminum, glass, iron and steel, and pulp and paper. The order in which the equations are presented follows the logic of the Fortran source code very closely to facilitate an understanding of the code and its structure. All subroutines are run for each year y, industry i, and each of the four census regions r unless otherwise

indicated. For variables disaggregated to the nine census divisions, the subscript d will be used to differentiate it from standard regional detail.

IND

IND is the main industrial subroutine called by the National Energy Modeling System (NEMS). This subroutine calls some data initialization subroutines, including one to retrieve energy price and macroeconomic data (Setup_Mac_and_Price) and routines to solve the model (ISEAM) and to export its results to NEMS global variables (WEXOG).

SETUP_MAC_AND_PRICE

In subroutine Setup_Mac_and_Price, the value of shipments data from the NEMS MAM is processed. Employment is also obtained from the Macroeconomic Activity Module (MAM) for each non-agricultural industry. Prices for the various fuels, as well as the previous year's consumption, are obtained from NEMS COMMON blocks. The IDM energy demand projections are benchmarked to values presented in the *Monthly Energy Review September 2013* in subroutine WEXOG. The national-level values are allocated to the census divisions using the *State Energy Data Report 2013*. Because detailed data for the IDM are available only for the four census regions, the energy prices obtained from NEMS (available for each of the nine census divisions) are combined using a weighted average of the fuel prices as shown in the following equation for the first model year. A similar weighted average is used for all other fuels and model years. However, the previous year's consumption is used rather than SEDS consumption. The price for purchased electricity is given by the following:

$$PRCX_{elec} = \frac{\sum_{d=1}^{Num_r} DPRCX_{elec,d} * QSELIN_{d,2013}}{\sum_{d=1}^{Num_r} QSELIN_{d,2013}} \qquad (1)$$

where

$PRCX_{elec}$ = Price for purchased electricity;

NUM_r = Number of census divisions in census region r;

$DPRCX_{elec,d}$ = Price of purchased electricity in census division d; and

$QSELIN_{d,2013}$ = SEDS consumption of electricity in census division d in 2013.

IND calls two subroutines: ISEAM, the subroutine that guides the IDM calculations, and WEXOG, the subroutine that reports the results back to NEMS. The other fuels are calculated in the same manner.

ISEAM

ISEAM controls all of the IDM calculations and initiates some input operations. It opens external files for debugging, binary files for restarting on successive iterations and projection years and opens the input data files. In the first model year and only on the first iteration, ISEAM calls RCNTRL to read the runtime

parameters file (INDRUN.TXT) and base-year boiler data (ITLBSHR.TXT). ISEAM also reads a data file, INDBEU.TXT, containing building energy use for lighting, heating, ventilation, and air conditioning. ISEAM calls REXOG to read in exogenous inputs on each model run. For the first model year, ISEAM calls the following subroutines for each census region within each industry: IEDATA, UECTPC, CALBYPROD, CALPATOT, CALBTOT, CALGEN, CALBSC, CALSTOT, and INDTOTAL. After the projection for the last census region for a particular industry has been calculated, the following two subroutines are called to compute totals: NATTOTAL and CONTAB. After the first model year, ISEAM calls two subroutines, RDBIN to read the restart files and MODCAL to carry out model calculations. After all model calculations have been completed, ISEAM calculates industry totals and saves information to the restart files in the subroutine WRBIN. Finally, after each industry has been processed, ISEAM calls the subroutines ADDUPCOGS and INDCGN to aggregate and report industrial cogeneration estimates to NEMS.

RCNTRL

RCNTRL reads data from the input files INDRUN.TXT and ITLBSHR.TXT. The INDRUN.TXT file contains internal control variables for the IDM. Data in this file are based on user-defined parameters consisting of indicator variables for subroutine tracing, debugging, writing summary tables, options to calculate model sensitivities, and benchmarking options. The ITLBSHR.TXT data contain estimated 2014 boiler energy use by fuel and is used for calculating boiler fuel shares.

IEDATA

IEDATA stands for Industrial ENPROD Data, where ENPROD.TXT is the name of the initial industrial input data file. This routine consists of many subprograms designed to retrieve industrial input data.

REXOG

REXOG prepares exogenous data obtained from MAM for use in the IDM. Dollar value of shipments and employment are aggregated over the appropriate census divisions to obtain data at the census region level. The macroeconomic variables used by the IDM are based on 2012 NAICS codes. Employment data is obtained from NEMS at the three-digit NAICS level. For some industries, employment data must be shared out among industries within a three-digit NAICS level.

IRHEADER

The IRHEADER subroutine imports industry and region identifier numbers, base-year values of output, physical-to-dollar-output conversion factors, and base-year steam demand.

It calculates the ratio of physical output to 2014 value of shipments for glass, cement, and aluminum industries. This constant ratio is applied to value of shipments for subsequent years. For the iron and steel industries, PHDRAT can vary from year to year, given as follows:

$$PHDRAT = \ PHYSICAL/PRODVX \tag{2}$$

where

$PHDRAT$ = Ratio of physical units to value of shipments;

$PHYSICAL$ = Physical units of output; and

$PRODVX$ = Value of shipments.

If the unit energy consumption (UEC) is in physical units, then the following equation is used:

$$PRODX = PRODVX * PHDRAT \qquad\qquad (3)$$

where

$PRODX$ = Output in physical units;

$PHDRAT$ = Ratio of physical units to value of shipments; and

$PRODVX$ = Value of shipments.

If the UEC is in dollar units, then no physical conversion is made, and PRODX is set equal to PRODVX.

MECSBASE

The MECSBASE subroutine imports production throughput coefficients, process step retirement rates, and other process step flow information from the file PRODFLOW.TXT. Imported process step flow data for each process step include process step number, number of links, the process steps linked to the current step, physical throughput to each process step, retirement rate, and process step name. A linkage is defined as a link between one or more process steps. The model simulates process steps for three of the energy-intensive industries that use the process flowsheet method: glass, cement and lime, and aluminum.

ISEAM

Gets building energy use data including lighting, HVAC, facility support, and onsite transportation from INDBEU.TXT.

IRBSCBYP

Gets byproduct fuel information for the boiler, steam, and cogeneration component. These data consist of fuel identifier numbers of steam intensity values.

RDCNTL

Reads INDRUN.TXT and ITLBSHR.TXT. The latter contains base year boiler-fuel use and is used to calculate boiler-fuel shares. Biomass data is retrieved in the IRBSCBYP routine.

IRCOGEN

Gets cogeneration information from file EXSTCAP.TXT, including capacity, generation, fuel use, and thermal output from 1990 through 2008. Gets corresponding data for planned units from file PLANCAP.TXT.

IRSTEPBYP

Gets byproduct data for process and assembly component. These data consist of fuel identifier numbers and heat intensity values.

UECTPC

Reads the industrial technology data file (ITECH.TXT) to update the initial ENPROD.TXT data file with 2014 values of UECs and TPCs. The second half of ITECH.TXT is reserved for use in side cases.

IFINLCALC

Calculates initial year values for process step production throughput for the energy-intensive industries.

Specialized subroutines

These subroutines perform calculations for energy consumption and write results that can be output and used by other modules of NEMS. Specialized subroutines calculate process and assembly energy for end-use manufacturing industries, steam allocation to boiler or CHP (except iron and steel and pulp and paper). The description of energy consumption calculations for non-manufacturing industries starts on page 83, and energy consumption calculations for process-flow industries (cement, aluminum, glass, iron and steel, and pulp and paper) starts on page 102.

CALPATOT

CALPATOT calculates the total energy consumption from the process and assembly (PA) component. Energy consumption at each process step is determined by multiplying the current production at that particular process step by the UEC for that process step.

The annual UEC for the old and new vintage is calculated as the product of the previous year's UEC and a factor that reflects the assumed rate of intensity decline over time and the impact of energy price changes on the assumed decline rate, given as follows:

$$Enpint_{v,f,s,y} = EnpintLag_{v,f,s,y} * (1 + TPCRate_v) \qquad (4)$$

where

$Enpint_{v,f,s}$	=	Unit energy consumption of fuel f at process step s for vintage v;
$EnpintLag_{v,f,s}$	=	Previous year's energy consumption of fuel f at process step s for vintage v; and

$$TPCRate_v \qquad\qquad = \text{Energy intensity decline rate for vintage } v \text{ after accounting for the impact of increased energy prices.}$$

The values for TPCRate$_v$ are calculated using the following relationships if the fuel price is higher than it was in 2014. Otherwise, the default value for the intensity decline rate (BCSC$_{v,f,s}$) is used.

$$Pricerat_y = \max\left(1, \frac{AvgPrice_y}{AvgPrice_{2014}}\right) \qquad\qquad (5)$$

$$TPCPriceFactor_y = \frac{Pricerat_y^{TPCBeta}}{1 + Pricerat_y^{TPCBeta}} \qquad\qquad (6)$$

$$TPCRate_{v,f,s,y} = 2 * TPCPriceFactor_y {}^* BCSC_{v,f,s} \qquad\qquad (7)$$

where

$Pricerat_y$ = Ratio of current year average industrial energy price to 2014 price;

$TPCBeta$ = Parameter of logistic function, currently specified as 4;

$TPCPriceFactor_y$ = TPC price factor, ranging from 0 (no price effect) to 2 for ENPINT;

$TPCRate_{v,f,s,y}$ = Intensity for capital of vintage v,v fuel f, step s, and year y after accounting for changes due to energy price changes for vintage v; and

$BCSC_{v,f,s}$ = Default intensity rate for old and new vintage v for each fuel f and step s.

The old vintage consists of capital in production in 2014 and is assumed to retire at a fixed rate each year. Middle vintage capital is that which is added from 2014 through the year *Year*-1, where *Year* is the current projection year. New capital is added for the projection years when existing production is less than the output projected by the MAM. Capital stock added during the projection period is retired in subsequent years at the same rate as the pre-2007 capital stock.

Estimates of existing old and middle vintage production are reduced by the retirement rate of capital through the equations, as follows:

$$RetirePriceFactor_y = \frac{Pricerat_y^{RetireBeta}}{\left(1 + Pricerat_y^{RetireBeta}\right)} \qquad\qquad (8)$$

$$RetireRate_{s,y} = 2 * RetirePriceFactor_y {}^* ProdRetr_s \qquad\qquad (9)$$

where

$Pricerat_y$ is defined on page 47;

$RetireBeta$ = Parameter of logistic function, currently specified as 2 for capital stock retirement;

$RetirePriceFactor_y$ = TPC price factor, ranging from 0 (no price effect) to 2;

$RetireRate_{s,y}$ = Retirement rate after accounting for energy price increases for step s; and

$ProdRetr_s$ = Default retirement rate for step s.

Energy consumption is calculated for each fuel, vintage, and step using the following equation:

$$ENPQTY_{v,f,s} = PRODCUR_{v,s} * ENPINT_{v,f,s} \tag{10}$$

where

$ENPQTY_{v,f,s}$ = Consumption of fuel f at process step s for vintage v;

$PRODCUR_{v,s}$ = Production at process step s, for vintage v; and

$ENPINT_{v,f,s}$ = Unit energy consumption of fuel f at process step s for vintage v.

Consumption of each fuel is converted to trillions of Btu. Energy consumption is subdivided into main fuels, intermediate fuels, and renewable fuels. The main fuel group includes the following:[31]

- o Purchased electricity
- o Core and non-core natural gas
- o Natural gas feedstocks
- o Steam coal
- o Coking coal (including net coke imports)
- o Residual oil
- o Distillate oil
- o Liquefied petroleum gas for heat and power
- o Liquefied petroleum gas for feedstocks
- o Motor gasoline
- o Still gas
- o Petroleum coke
- o Asphalt and road oil
- o Petrochemical feedstocks
- o Other petroleum feedstocks
- o Other petroleum

The intermediate fuel group includes the following:

- o Steam
- o Coke oven gas
- o Blast furnace gas

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[31]Still gas and petroleum coke are consumed primarily in the refining industry, which is modeled in the Liquid Fuels Market Module of NEMS.

      ○   Other byproduct gas
      ○   Waste heat
      ○   Coke

The renewable fuels group represented in the model includes the following:

- Hydropower
- Biomass—wood
- Biomass—pulping liquor
- Municipal solid waste

Geothermal, solar, and wind are currently not represented in the model because of their low industrial penetration.

Energy consumption for the three fuel groups is determined for each fuel by summing over the process steps and the three vintage categories, as shown below for main fuels. The equations for intermediate and renewable fuels are similar, as shown by the following:

$$ENPMQTY_f = \sum_{s=1}^{MPASTP} \sum_{v=1}^{3} ENPQTY_{v,f,s} \qquad (11)$$

where

$\quad ENPMQTY_f \quad$ = Consumption of main fuel f in the process and assembly component;

$\quad MPASTP \quad$ = Number of process step s; and

$\quad ENPQTY_{v,f,s} \quad$ = Consumption of fuel f at process step s for all vintages v.

The impact of increased corn-based ethanol production on energy used in agriculture and in producing nitrogenous fertilizer is projected as follows:

$$CORNFUEL_f = \sum_{f=1}^{6} CORNFAC_f * CORNINCR \qquad (12)$$

where

$\quad CORNFUEL_f \quad$ = Consumption of fuel f in agricultural production for ethanolfeedstocks;

$\quad CORNFAC_f \quad$ = Thousand Btu of fuel f to produce 1 bushel of corn; and

$\quad CORNINCR \quad$ = Incremental corn production.

The fuels, f, are electricity, natural gas, distillate, natural gas liquids (NGL), motor gasoline, and natural gas used for additional fertilizer production.

The increased fuel requirements are then added to the energy projections for the agricultural crops industry (NAICS 111), and, for fertilizer, to the agricultural chemicals industry (NAICS 3253).

Energy consumption for coke imports is calculated as the difference between coke consumption and coke production. In the current IDM, coke is consumed only in the BF/BOF process step in the iron and steel industry. Coke is produced only in the coke oven process step in the iron and steel industry. The equation for net coke imports is shown below:

$$ENPMQTY_{coke} = ENPIQTY_{coke} - \left(PRODCUR_{total,co} * \frac{24.8}{10^6}\right) \qquad (13)$$

Where

$ENPMQTY_{coke}$ = Quantity of coke imports in the PA component;

$ENPIQTY_{coke}$ = Consumption of coke in the PA component;

$PRODCUR_{total,co}$ = Current production at the coke oven process step for all vintages; and

$24.8/10^6$ = Unit conversion factor, of heat content per short ton of coke.

MOTORS

Subroutine MOTORS uses a motor stock model, which is described on page 16, to calculate machine drive energy consumption for these end-use manufacturing industries: food, bulk chemicals, metal-based durables, and the balance of manufacturing. The Energy Independence and Security Act of 2007 (EISA2007) increased motor efficiency standards, effective no later than 2011. The motor stock model has been revised to reflect this and the fact that the Energy Policy Act of (EPACT92) standards no longer apply. The motor stock model is a stock model that tracks the number of motors in each of these four industries for seven size groups as shown in Table 3 on page 16. The first step is to initialize the following variables for their base year (2002) values, as follows:

where

$MotorStock_{g,2002}$ = Motor stock for motor size group g in the base year (2002), number of motors;

$MotAvgEnergy_{g,2002}$ = Average energy consumption per motor for motor size group g in the base year (2002), kWh per motor per year;

$MotAvgEff_{g,2002}$ = Average motor energy efficiency rating for motor size group g in the base year (2002);

$FailurePct_g$ = Percentage of motors that fail each year for motor size group g;

$MotorRetPct_g$ = Percentage of motors retired upon failure for motor size group g;

$MotorRewDrop_g$ = Drop in efficiency for rewound motors in motor size group g;

$$MotorSysLife_g \qquad = \quad \text{Motor system efficiency program life in motor size group } g;$$

$$PumpAppPct_g \qquad = \quad \text{Motor system efficiency applicability, percentage of pump systems in motor size group } g;$$

$$FanAppPct_g \qquad = \quad \text{Motor system efficiency applicability, percentage of fan systems in motor size group } g;$$

$$CompAppPct_g \qquad = \quad \text{Motor system efficiency applicability, percentage of compressor systems in motor size group } g;$$

$$PumpSavPct_g \qquad = \quad \text{Motor system efficiency savings fraction for pump systems in motor size group } g;$$

$$FanSavPct_g \qquad = \quad \text{Motor system efficiency savings fraction for fan systems in motor size group } g; \text{ and}$$

$$CompSavPct_g \qquad = \quad \text{Motor system efficiency savings fraction for compressor systems in motor size group } g.$$

Once these variables have been initialized, the base year energy consumption is calculated as follows:

$$TotalMotorEnergy_{g,y} \;=\; MotorStock_{g,y} \;*\; \left(MotorAvgEnergy_{g,2014} \;*\; \frac{3412}{10^{12}} \right) \qquad (14)$$

where

$$TotalMotorEnergy_{g,2014} = \quad \text{Motor energy consumption in trillion Btu for motor size group } g \text{ in the base year (2014); and}$$

$MotorStock_{g,y}$ and $MotAvgEnergy_{g,y}$ are defined above.

Projections of the motor stock, and the associated energy consumption, are grounded in these initial base year values. The growth in the value of shipments for each industry provided by the MAM is the driving force determining the overall stock of motors. New motors are purchased to accommodate the projected industrial growth, as well as to replace retired motors. The number of motors retired upon failure is evaluated using a cost and performance algorithm. The initial cost differential for replacing the failed motor is weighed against the energy expenditure savings to determine the payback period in years. A payback acceptance curve provides the split between replaced and repaired motors. The first calculation is the price differential for the new motor, as follows:

$$ReplacePrPrem_g \;=\; \left[PEListPrice_g \;*\; (1 - DealerDisc) \right] \;-\; RewindCost_g \quad (15)$$

where

$$ReplacePrPrem_g \qquad = \quad \text{Premium for replacing a failed motor for motor size group } g;$$

$$PEListPrice_g \qquad = \quad \text{The manufacturer's list price for an EISA efficiency motor in motor size group } g;$$

$DealerDisc$	=	The average dealer discount offered on purchases of EISA efficiency motors; and
$RewindCost_g$	=	The cost to rewind a failed motor for motor size group g.

The energy expenditure savings are calculated, with prices in 2002 dollars for convenience, as follows:

$$ReplaceAnnSav_g = MotorHP_g * HPtoKW * MotorOpHr_g$$

$$* IndElecPrice * \left[\left(\frac{1}{RewoundEff_g} \right) - \left(\frac{1}{PEPctEff_g} \right) \right] \qquad (16)$$

where

$ReplaceAnnSav_g$	=	The expected annual savings from the replacing a failed motor with a minimum efficiency motor for motor size group s, in 2002 dollars;
$MotorHP_g$	=	The rated motor horsepower for motor size group g;
$HPtoKW$	=	The conversion factor from horsepower to kilowatts;
$MotorOpHr_g$	=	The annual operating hours for motors in motor size group g;
$IndElecPrice$	=	The industrial purchased electricity price in 2002 dollars per kWh;
$RewoundEff_g$	=	The efficiency rating for a rewound motor for motor size group g; and
$PEPctEff_g$	=	The efficiency rating for an EISA minimum efficiency motor for motor size group g.

The simple payback period in years y is estimated as follows:

$$ReplacePayback_{g,y} = \frac{ReplacePrPrem_g}{ReplaceAnnSav_g / (1 + disrate)^y} \qquad (17)$$

where

$disrate$	=	Real discount rate, which is the 10-year Treasury bill rate adjusted for risk;
$ReplacePayback_g$	=	Payback period, rounded to nearest year, for replacing a failed motor with a minimum efficiency motor purchased for motor size group g; and

$ReplacePrPrem_g$ and $ReplaceAnnSav_g$ are defined above.

Given the payback calculated for each industry and motor size group, the model estimates the number of failed motors that are replaced with EISA minimum efficiency motors and the number of failed motors that are repaired. This calculation uses an assumed distribution of required investment payback periods referred to as the payback acceptance curve. Rather than using an actual curve, a table of assumed acceptance rates is used for each integer payback period from zero to four years. To obtain an acceptance fraction, or economic fraction, from a non-integer value for payback, a linear interpolation is done. The economic fraction is determined from a lookup table and interpolation function called *Acceptance*, given the table of acceptance fractions, the five acceptance rates, and the payback period for the motor size group, as follows:

$$ReplaceAccept_g = Acceptance(PremAccept, 5, ReplacePayback_g) \tag{18}$$

where

$ReplaceAccept_g$ =   Fraction of premium efficiency motors purchased in motor size group *s* based on payback period acceptance assumptions;

$PremAccept$ =   Array of payback acceptance rates corresponding to integer payback periods ranging from zero to four (a total of five rates); and

$ReplacePayback_g$ is defined above.

The number of failed motors is given by the following:

$$FailedMotors_{g,y} = MotorStock_{g,y-1} * FailurePct_g \tag{19}$$

Finally, the number of motors purchased to replace failed motors is given by the following:

$$RepMotorFlow_{g,y} = FailedMotors_{g,y-1} * ReplaceAccept_g \tag{20}$$

where

$RepMotorFlow_{g,y}$ =   Number of new motors purchased to replace failed motors in motor size group *g* based on payback period acceptance assumptions; and

$FailedMotors_{g,y} \text{ and } ReplaceAccept_g$ are defined above.

Motor stock changes are as follows:

$$TotalMotorFlow_{g,y} = MotorStock_{g,y-1} * IndShipGr_y + RepMotorFlow_{g,y} \tag{21}$$

where

$TotalMotorFlow_g$ = New motors purchased for motor size group *g*;

$IndShipGr$ = Growth from previous year in industrial value of shipments; and

$MotorStock_{g,y-1} \text{ and } RepMotorFlow_{g,y}$ are defined above with motor stock by industry i .

The new motor stock is then given as follows:

$$MotorStock_{g,y} = MotorStock_{g,y-1} - FailedMotors_{g,y} + RewoundMotors_{g,y} + TotalMotorFlow_{g,y} \quad (22)$$

In order to track the various vintages with their differing efficiencies, one additional calculation is required, as follows:

$$RewoundMotors_{g,y} = FailedMotors_{g,y} * RepMotFlow_g \quad (23)$$

where

$RewoundMotors_{g,y}$ = Number of motors rewound for motor size group g and year y; and

$FailedMotors_{g,y}$ and $RepMotorFlow_g$ are defined above.

When motors are rewound, there is generally a drop in efficiency. The magnitude of the efficiency decline can be specified by the user. The equation to calculate the efficiency of rewound motors is given as follows:

$$RewoundEff_g = MotAvgEff_{g,y-1} - MotRewDrop_g \quad (24)$$

where

$RewoundEff_g$ = The efficiency of rewound motors for motor size group g;

$MotRewDrop_g$ = The user specified drop in efficiency for rewound motors in motor size group s; and

$MotAvgEff_{g,y-1}$ is defined above.

The average efficiency of new motors is calculated as a weighted average efficiency of the motors purchased, as follows:

$$NewMotorEff_{g,y} = (PEPctEff_g * PremMotorFlow_{g,y})/RepMotFlow_{g,y} \quad (25)$$

where

$NewMotorEff_g$ = The average efficiency of new motors for motor size group s; and

$PEPctEff_{gs}, PremMotorFlow_g, and RepMotFlow_g$ are defined above.

The average amount of energy consumed by the new motors purchased is given by the following:

$NewMotorEnergy_g$

$$= MotAdjEnergy_{g,y-1} * \left(1 - \frac{(NewMotorEff_g - MotAvgEff_{g,y-1})}{NewMotorEff_g}\right) \quad (26)$$

where

$NewMotorEnergy_g$ = The average energy consumed by new motors for motor size group g in kWh per motor per year;

$MotAdjEnergy_{g,y-1}$ = The adjusted average energy consumed by motors for motor size group g and year $y-1$ in kWh per motor per year (the process used to adjust the average energy is described below); and

$NewMotorEff_g$ and $MotAvgEff_{g,y-1}$ are defined above.

The average amount of energy consumed by the rewound motors is given by the following:

$$RewMotorEnergy_{g,y} = MotAdjEnergy_{g,y-1} * \left(1 - \frac{RewoundEff_g - MotAvgEff_{g,y-1}}{RewoundEff_g}\right) \quad (\,27\,)$$

where

$RewMotorEnergy_{g,y}$ = The average energy consumed by rewound motors for motor size group g in kWh per motor for year y;

$MotAdjEnergy_{g,y-1}$ = The adjusted average energy consumed by motors for motor size group g and year $y-1$ in kWh per motor per year (the process used to adjust the average energy is described below); and

$RewoundEff_g$ and $MotAvgEff_{g,y-1}$ are defined above.

The average amount of energy consumed by all motors in the stock is given by the following:

$$MotAvgEnergy_{g,y} = \frac{\begin{pmatrix} MotAdjEnergy_{g,y-1} * \\ \left(MotorStock_{g,y} - FailedMotors_{g,y}\right) \\ + \left(TotalMotorFlow_{g,y} * NewMotorEnergy_g\right) \\ + \left(RewoundMotors_{g,y} * RewMotorEnergy_g\right) \end{pmatrix}}{MotorStock_{g,y}} \quad (28\,)$$

where

$MotAvgEnergy_y$ = The average energy consumed by all motors for motor size group g in kWh per motor per year;

$MotAdjEnergy_{g,y-1}$ = The adjusted average energy consumed by motors for motor size group g and year $y-1$ in kWh per motor per year (the process used to adjust the average energy is described below); and

$MotorStock_{g,y-1}, FailedMotors_g, TotalMotorFlow_g, NewMotorEnergy_g, RewoundMotors_g,$ $RewMotorEnergy_y,$ and $MotAdjEnergy_{g,y-1}$ are defined above.

The average energy efficiency of the stock of motors is given by the following:

$$RewoundEff_g = MotAvgEff_{g,y-1} - MotRewDrop_g \tag{29}$$

where

$MotAvgEff_g$ = The average energy efficiency of motors for motor size group g; and

$RewoundEff_g$ and $MotRewDrop_g$ are defined above.

The energy efficiency of motor systems is affected not only by the efficiency of the motors themselves but also by the efficiency of the systems in which the motors are used. The three largest categories of motor systems are pump systems, fan systems, and compressor systems. The following equation calculates the overall motor system energy consumption savings rate:

$$SystemSavingsR_g = \frac{\begin{pmatrix} (PumpAppPct_g * PumpSavPct_g) \\ + (FanAppPct_g * FanSavPct_g) \\ + (CompAppPct_g * CompSavPct_g) \end{pmatrix}}{MotSysLife_g} \tag{30}$$

where

$SystemSavingsR_g$ = The overall savings rate from pump, fan, and compressor system efficiency improvements for motor size group g;

$PumpAppPct_g$ = Motor system efficiency applicability, percentage of pump systems in motor size group g;

$PumpSavPct_g$ = Motor system efficiency savings fraction for pump systems in motor size group g;

$FanAppPct_g$ = Motor system efficiency applicability, percentage of fan systems in motor size group g;

$FanSavPct_g$ = Motor system efficiency savings fraction for fan systems in motor size group g;

$CompAppPct_g$ = Motor system efficiency applicability, percentage of compressor systems in motor size group g;

$CompSavPct_g$ = Motor system efficiency savings fraction for compressor systems in motor size group g; and

$MotorSysLife_g$ = Motor system efficiency improvement life in years for motors in motor size group g.

Applying the overall motor system energy savings percentage to the total energy consumption for the motor stock results in the total energy consumption by motor systems, given as follows:

$$MotAdjEnergy_{g,y} = MotAvgEnergy_{g,y} * (1 - SystemSavingsR_g) \tag{31}$$

where

$MotAdjEnergy_{g,y}$ = The adjusted average energy consumption of the motor stock for motor size group *s* in kWh per motor per year; and

$MotorAvgEnergy_{g,y}$ and $SystemSavingsR_g$ are defined above.

The total amount of energy is calculated for the stock and is converted from gigawatthours to trillion Btu, as follows:

$$TotalMotorEnergy_{g,y} = (MotorStock_{g,y} * MotorAvgEnergy_{g,y}) * \frac{3412}{10^{12}} \tag{32}$$

where

$TotalMotorEnergy_{g,y}$= The total motor energy consumption of the motor stock for motor size group *g* in trillion Btu per year; and

$MotorStock_{g,y}$ and $MotorAvgEnergy_{g,y}$ are defined above.

Finally, the adjusted total amount of energy is calculated for the stock and is converted from gigawatthours to trillion Btu, as follows:

$$TotalAdjMotorEnergy_{g,y} = (MotorStock_{g,y} * MotAdjEnergy_{g,y}) * \frac{3412}{10^{12}} \tag{33}$$

where

$TotalAdjMotorEnergy_g$ = The total adjusted motor energy consumption of the motor stock for motor size group *s* in trillion Btu per year; and

$MotorStock_g$ and $MotorAdjEnergy_g$ are defined above.

CALBTOT

CALBTOT calculates the total energy consumption for the buildings portion of the IDM. Building energy consumption is calculated for three building uses: lighting; heating, ventilation, and air conditioning (HVAC); and onsite transportation. Total energy consumption is determined as a weighted average of the industry employment UEC and the industry output UEC, as follows:

$$ENBQTY_{e,f} = \begin{pmatrix} EWeight^*[EMPLX^*ENBINT_{e.f}] \\ + PWeight * [ProdVX^*ONBINT_{e,f}] \end{pmatrix} * BldPFac \tag{34}$$

where

$ENBQTY_{e,f}$ = Consumption of fuel *f* for building end use *e*;

$EMPLX$ = Employment;

$ProdVX$	=	Output;
$ENBINT_{e,f}$	=	Employment unit energy consumption (Btu per employee) of fuel f for building end use e;
$ONBINT_{e,f}$	=	Output unit energy consumption of fuel fuel f for building end use e;
$EWeight$	=	Weight for employment unit energy consumption (0.7);
$PWeight$	=	Weight for output unit energy consumption (0.3); and
$BldPFac$	=	Effect of energy price increases on buildings energy consumption.

The $BldPFac$ variable adjusts buildings energy consumption if the average industrial energy price increases above a threshold. Below the threshold, $BldPFac$ is equal to 1. Above the threshold, the value of $BldPFac$ is calculated as follows:

$$BldPFac = BldPRat^{BldElas} \qquad\qquad (35)$$

where

$BldPRat$	=	Ratio of current year's average industrial energy price to 2014 price; and
$BldElas$	=	Assumed elasticity, currently -0.5.

CALGEN

Subroutine CALGEN accounts for electricity generation from cogeneration. It combines estimated existing and planned cogeneration with new projected cogeneration based on an endogenous economic and engineering evaluation. The subroutine estimates market penetration of new (not currently planned) cogeneration capacity as a function of steam load, steam already met through cogeneration, and cost and performance factors affecting cogeneration economics. CALGEN calls subroutine COGENT to read in the cogeneration assumptions and calls subroutine EvalCogen to evaluate the economics of prototypical cogeneration systems sized to match steam loads in four size ranges. A function, *SteamSeg*, is also called to access a size distribution of steam loads for each industry. Generation for own use and electricity sales to the grid are calculated based on total generation and the shares of sales to the grid reported on Form EIA-860 data.[32]

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[32]Several subroutines not shown here perform the calculations required to initialize, aggregate, and summarize the cogeneration data derived from EIA-860, EIA-923, and predecessor EIA surveys and to incorporate changes from model additions. These subroutines include IRCOGEN, COGINIT, MECSLESS860, and ADDUPCOGS.

CALGEN begins by computing total steam demand as the sum of steam use in buildings (HVAC being the only system using steam) and steam use from the process and assembly component, as follows:[33]

$$\boldsymbol{S}TEMCUR = ENBQTY_{hvac,steam} + ENPIQTY_{steam} \tag{36}$$

where

$STEMCUR$	=	Total steam demand;
$ENBQTY_{hvac,steam}$	=	Consumption of steam for HVAC; and
$ENPIQTY_{steam}$	=	Consumption of steam in the process and assembly component.

Next, the portion of steam requirements that could be met by new cogeneration plants, up to the current model year, is determined as follows:

$$NonCogSteam = STEMCUR - CogSteam \tag{37}$$

where

$NonCogSteam$	=	Non-cogenerated steam based on existing cogeneration capacity;
$STEMCUR$	=	Total steam demand; and
$CogSteam$	=	Steam met by existing cogeneration units as of the last data year.

Non-cogeneration steam uses are disaggregated into eight size ranges, or segments, based on an exogenous data set providing the boiler size distribution for each industry. These data are accessed through the function $SteamSeg_{loadsegment}$. Steam load segments are assumed to be distributed in the same proportions as boiler capacity, as follows:

$$AggSteamLoad_{loadsegment} = NonCogSteam * SteamSeg_{loadsegment} \tag{38}$$

where

$AggSteamLoad_{loadsegment}$	= Steam demand for a given load segment;
$NonCogSteam$	= Non-cogenerated steam based on existing cogeneration capacity; and
$SteamSeg_{loadsegment}$	= The fraction of total steam in each of eight boiler firing ranges, in million Btu/hour, with the ranges being 1.5-3, 3-6.5, 6.5-10, 10-50, 50-100, 100-250, 250-500, and >500.

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[33]This subroutine also calculates the amount of steam produced by byproduct fuels, which reduces the amount of steam required to be produced by purchased fuels.

The average hourly steam load, $AvgHourlyLoad_{loadsegment}$ in each segment is calculated from the aggregate steam load, $AggSteamLoad_{loadsegment}$, based on 8,760 operating hours per year and converting from trillions to millions of Btu per hour, as follows:

$$AveHourlyLoad_{loadsegment} = \frac{AggSteamLoad_{loadsegment}}{0.008760} \qquad (39)$$

The maximum technical potential for cogeneration is calculated assuming all non-cogeneration steam demand for each load segment is converted to cogeneration. This calculation assumes that the technical potential is based on sizing systems, on average, to meet the average hourly steam load in each load segment. The number of system/segment options is *nsys*, currently 8, with each system indicated by the subscript *isys*. Using the power-steam ratio of the prototype cogeneration system selected for each load segment (from subroutine EvalCogen) this calculation is given as follows:

$$TechPot_{loadsegment} = AvgHourlyLoad_{loadsegment} * PowerSteam_{isys} \qquad (40)$$

where

$TechPot_{loadsegment}$ =   Technical potential for cogeneration, in megawatts, for a load segment, irrespective of the economics;

$AveHourlyLoad_{loadsegment}$ = Average hourly steam load in each load segment; and

$PowerSteam_{isys}$ =   Power-Steam ratio of the cogeneration unit, $isys$, which equivalent to the ratio of electrical efficiency to thermal efficiency.

The economic potential for cogeneration is estimated from the technical potential by applying the estimated fraction of that potential that will be realized over an extended time period, based on market acceptance criteria (as applied in subroutine EvalCogen), as follows:

$$EconPot_{loadsegment} = TechPot_{loadsegment} * EconFrac_{loadsegment} \qquad (41)$$

where

$EconPot_{loadsegment}$ = Economic potential for cogeneration in megawatts;

$TechPot_{loadsegment}$ = Technical potential for cogeneration, in megawatts, for a load segment if all cogeneration was adopted, irrespective of the economics; and

$EconFrac_{loadsegment}$ = Economic fraction based on the payback period and the assumed payback acceptance curve.

Given the total economic potential for cogeneration, the amount of capacity that would be added in the current model year is given by the following:

$$CapAddMW_{loadsegment} = EconPot_{loadsegment} * PenetrationRate \qquad (42)$$

where

$CapAddMW_{loadsegment}$ = Cogeneration capacity added, in megawatts, for a load segment;

$EconPot_{loadsegment}$ = Economic potential for cogeneration in megawatts; and

$PenetrationRate$ = Constant annual rate of penetration, assumed to be 5% based on the economic potential being adopted over a 20-year time period; also includes collaboration coefficients provided by the American Council for an Energy-Efficient Economy (ACEEE)[34] that show the relative likelihood of CHP adoption among U.S. regions.

Based on the results of a study performed for EIA,[35] which includes cogeneration system cost and performance characteristics, capacity additions are assumed to be natural-gas-fired except in certain industries that are known to use biomass for existing CHP, notably pulp and paper products. The corresponding generation and fuel use from these aggregated capacity additions are calculated from the assumed capacity factors and heat rates of the prototypical systems. The energy characteristics of the additions are used to increment the model's cogeneration data arrays: capacity (COGCAP), generation (COGGEN), thermal output (COGTHR) and electricity-related-fuel use (COGELF). These arrays are all indexed by census division, year, industry, and fuel. Since the model runs at the census region level, regional results are shared equally among the census divisions using a factor, $DSHR$, where $DSHR$ is either one half or one-third. The assignment statements to increment the arrays are as follows:

$$COGGEN_{d,ngas,y} = COGGEN_{d,ngas,y-1} + \qquad CAPADDGWH * DSHR \tag{43}$$

$$COGCAP_{d,ngas,t} = COGCAP_{d,ngas,y-1} + CAPADDGWH * DSHR \tag{44}$$

$$COGTHR_{d,ngas,y} = COGTHR_{d,ngas,y-1} + STMADDTRIL * DSHR \tag{45}$$

$$COGELF_{d,ngas,y}$$

$$= COGELF_{d,ngas,y-1} * \left(\left(CAPADDGWH * AVEHTRT/_{10^6} \right) - \left(STMADDTRIL/_{0.8} \right) \right) * DSHR \tag{46}$$

where

$CAPADDGWH$ = Generation from new capacity in gigawatthours;

$STMADDTRIL$ = Thermal (steam) output of new capacity in trillion Btu;

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[34] American Council for an Energy-Efficient Economy, "Challenges Facing Combined Heat and Power Today: A State-by-State Assessment," September 2011, http://aceee.org/research-report/ie111, and U.S. Energy Information Administration, Office of Energy Analysis.

[35] SENTECH Inc., *Commercial and Industrial CHP Technology Cost and Performance Data for EIA*, report prepared for the Office of Integrated Analysis and Forecasting, Energy Information Administration, Washington, DC, June 2014.

$AVEHTRT$ = Heat rate, or total fuel use per unit of generation in Btu/kWh.

Cogeneration from biomass (*BIO*) is also directly related to the amount of biomass available for that industry (calculated in subroutine CALBYPROD), which is calculated as follows:

$$BIO_y = MAX\left(0, \frac{BioAvail_y - BioAvail_{y-1}}{HeatRate}\right) \qquad (47)$$

where

$BioAvail_y$ = Biomass available for generation in model year y;

$BioAvail_{y-1}$ = Biomass available in the previous model year $y-1$; and

$HeatRate$ = Converts Btu to kWh (assumed to be 25,000 through 2003 and decline linearly to 17,000 by 2020).

The available biomass generation is then added to the current year's cogeneration arrays by the following calculation (incremental assignment shown) as follows:

$$COGGEN_{d,biomass,y} = COGGEN_{d,biomass} + BIO^*DSHR \qquad (48)$$

where

$COGGEN_{d,biomass}$ = Total biomass cogeneration by census division d; and

$DSHR$ = Factor to share census region addition to census divisions such that each division gets an equal share.

The biomass capacity, thermal output, and electricity-related fuel use associated with the generation (*BIO*) are used to increment the corresponding cogeneration data arrays, COGCAP, COGTHR, and COGELF.

Once the energy input and output characteristics of the cogeneration capacity additions have been combined with those of the existing capacity, the effect of cogeneration on purchased electricity demand and conventional fuel use can be determined.

The cogeneration capacity values (*COGCAP*) are used only for reporting purposes and not used within the IDM. The thermal output and fuel use from cogeneration, derived from arrays *COGTHR* and *COGELF*, are used in subroutine CALSTOT (see below) to determine the balance of the industry's steam demand that must be met by conventional boilers, and then combined with boiler fuel use to estimate total boiler, steam, and cogeneration (BSC) component energy requirements.

The amount of cogenerated electricity used on site (own-use) is estimated, with the balance of total electricity needs met from purchased electricity. The shares of electricity generation for grid sales and own-use are derived from Form EIA-860 survey data and are assumed to remain constant for existing capacity. The grid share for each census division, industry, and fuel, by year, is maintained in array $COGGRD_{d,f}$. In most industries, capacity additions are assumed to have the same grid/own-use shares as

that of the average (across regions) of the existing capacity in the last complete data year (2008). For the two industries in which cogeneration has already penetrated extensively (Food and Bulk Chemicals), a higher grid-sales share of 60% is assumed. As capacity is added, the average grid-sales share for each region and industry (*COGGRD*) is recomputed as follows:

$$NEWGEN_{d,f} = CapAddGWH_f * DSHR_d \tag{49}$$

$$OLDGRD_{d,f} = COGGEN_{d,f} + COGGRD_{d,f} \tag{50}$$

$$NEWGRD_{d,f} = NEWGEN_{d,f} * COGGRDNEW_d \tag{51}$$

$$COGGRD_{d,f} = \frac{\left(OLDGRD_{d,f} + NEWGRD_{d,f}\right)}{\left(COGGEN_{d,f} + NEWGEN_{d,f}\right)} \tag{52}$$

Electricity generation for own use is then calculated as follows:

$$ELOWN = \sum_d \sum_f \left(COGGEN_{d,f} + COGGRD_{d,f}\right) \tag{53}$$

where

$ELOWN$ = Electricity generation for own use;

$COGGEN_{d,f}$ and $COGGRD_{d,f}$ are defined above; and

Electricity generation for sales to the grid is calculated similarly.

EvalCogen

Subroutine EvalCogen is called by subroutine CALGEN to evaluate a set of prototype cogeneration systems sized to match steam loads in eight size ranges, or load segments. The thermal capacities of the systems are assigned to approximately match the average boiler size in each industry for each of the following ranges (in million Btu per hour): 1.5-3, 3-6.5, 6.5-10, 10-50, 50-100, 100-250, 250-500, and >500. The corresponding steam output, or steam load, is determined from the average boiler capacity as follows:

$$SteamLoad_{loadsegment} = AveBoilSize_{loadsegment} * EboilEff_{loadsegment} \tag{54}$$

where

$SteamLoad_{loadsegment}$ = Steam output of average boiler in the load segment, in million Btu per hour;

$AveBoilSize_{loadsegment}$ = Firing capacity of average boiler in the load segment; and

$EboilEff_{loadsegment}$ = Assumed boiler efficiency.

For each load segment, the model preselects a candidate cogeneration system with thermal output that roughly matches the steam output of the average-sized boiler in the load segment. The model relies on the following user-supplied set of characteristics for each cogeneration system, as follows:

$CogSizeKW_{isys}$ = Net electric generation capacity in kilowatts;

$CogCapCostKW_{isys}$ = Total installed cost, in 2005 dollars per kilowatthour;

$CapFac_{isys}$ = System capacity factor;

$CHeatRate_{isys}$ = Total fuel use per kilowatthour generated (Btu/kWh); and

$OverAllEff_{isys}$ = Fraction of input energy converted to useful heat and power.

From the above user-supplied characteristics, the following additional parameters for each system are derived:

$ElecGenEff_{isys}$ = Fraction of input energy converted to electric energy, or electric energy efficiency;

$\approx 3412 / CHeatRate_{isys}$

$ElecSizeMWh_{isys}$ = Electric generation from the cogeneration plant in megawatthours;

$\approx CogSizeKW_{isys} * 8.76 * CapFac_{isys}$

$FuelUse_{isys}$ = Cogeneration system fuel use per year in billion Btu;

$\approx ElecSizeMWh_{isys} * CHeatRate_{isys} / 10^6$

$PowerSteam_{isys}$ = Ratio of electric power output to thermal output;

$\approx ElecGenEff_{isys} / (OverAllEff_{isys} - ElecGenEff_{isys})$

$SteamOutput_{isys}$ = Thermal output of the cogeneration system in million British thermal units (MMBtu) per hour; and

$$\approx CogSizeKW_{isys} * 0.003412 / PowerSteam_{isys}$$

$disrate$ = Real discount rate, which is the 10-year Treasury bill rate adjusted for risk.

For consistency the system number for each steam load segment is the same as the subscript *isys*:

$$CogSys_{loadsegment} = isys \tag{55}$$

Next, the model estimates investment payback period (*Cpayback_loadsegment*) required to recover the aggregate cogeneration investment for each load segment. This figure is determined by estimating the annual cash flow from the investment, defined as the value of the cogenerated electricity, less the cost of the incremental fuel required for generation. For this purpose, the annual cost of fuel (natural gas) and the value of the electricity are based on the prices averaged over the first 10 years of operating the cogeneration system. The electricity is valued at the average industrial electricity price in the region, net of standby charges that would be incurred after installing cogeneration (*CogElecPrice*).

The standby charges are assumed to be the user-specified fraction of the industrial electricity rate (10%). For natural gas (*CogFuelPrice*), the price of firm-contract natural gas was assumed to apply. The steps performed in each annual model loop are as follows:

Determine annual fuel cost of the aggregated cogeneration systems in each load segment:

$$FuelCost_{loadsegment} = FuelUse_{isys} * CogFuelPrice \tag{56}$$

Determine the annual fuel use and cost of operating the existing system (conventional boiler):

$$ExistFuelUse_{loadsegment} = \frac{SteamOutput_{isys}*8.76*CapFac_{isys}}{EboilEff_{loadsegment}} \tag{57}$$

$$ExistFuelCost_{loadsegment} = ExistFuelUse_{loadsegment} * CogFuelPrice \tag{58}$$

Determine incremental fuel cost and the value of cogenerated electricity:

$$IncrFuelCost_{loadsegment} = FuelCost_{loadsegment} - ExistFuelCost_{loadsegment} \tag{59}$$

$$ElecValue_{loadsegment} = ElecSizeMWh_{isys} * CogElecPrice * 0.003412 \tag{60}$$

Determine the cash flow, or operating profit, of the investment:

$$OperProfit_{loadsegment} = ElecValue_{loadsegment} - IncrFuelCost_{loadsegment} \tag{61}$$

Determine the investment capital cost and the investment payback period:

$$Investment_{loadsegment} = CogSizeKW_{isys} * CogCapCostKW_{isys} \tag{62}$$

$$CPayBack_{loadsegment,y} = \frac{Investment_{loadsegment}}{OperProfit_{loadsegment} \frac{1}{(1+disrate)^y}} \tag{63}$$

Given the payback for the aggregated system evaluated for each load segment, the model estimates the fraction of total technical potential considered economical. This calculation uses an assumed distribution of required investment payback periods, referred to as the payback acceptance curve. A table of assumptions is used containing acceptance rates for each integer payback period from 0 to 12 years. To obtain an acceptance fraction, or economic fraction, from a non-integer value for payback, a linear interpolation is done. The economic fraction is determined from a table lookup and interpolation function called *Acceptance*.

Given the table of acceptance fractions, the number of rows in the table (13), and the payback period for the load segment, the calculation is

$$EconFrac_{loadsegment} = Acceptance\left(AcceptFrac, 13, CPayBack_{loadsegment}\right) \tag{64}$$

where

$EconFrac_{loadsegment}$ = Fraction of cogeneration investments adopted based on payback period of acceptance assumptions;

$AcceptFrac$ = Array of payback acceptance rates corresponding to integer payback periods ranging from 0 to 12 (13 rates altogether); and

$CPayBack_{loadsegment}$ = Cogeneration investment payback period.

CALSTOT

CALSTOT calculates total fuel consumption in the boiler, steam, and cogeneration (BSC) component based on total steam demand within an industry (*STEMCUR*). Steam demand and fuel consumption (in BTU) are allocated between cogeneration and conventional boilers. Fuel use and steam demand from cogeneration, calculated in subroutine CALGEN, are treated as inputs to this subroutine.

Steam from cogeneration (*COGSTEAM*) is obtained by summing the cogeneration thermal output (in array *COGTHR*) across fuels and census divisions. Steam demand to be met by conventional boilers (*NonCOGSTEAM*) is equal to total steam demand (*STEMCUR*) minus cogeneration steam (*COGSTEAM*) production.

The estimated consumption of fuel for cogeneration is stored in two variables: fuel used to generate electricity (*COGELF*) and fuel associated with the thermal output (*COGTHR*). The fuel associated with the thermal output assumes a hypothetical 80% efficiency, so it is computed as *COGTHR* divided by 0.8. Thus, total cogeneration system fuel use, *FuelSys_f*, is given by the following:

$$FuelSys_f = \sum_d COGELF_{d,f} + \left(COGOTHR_{d,f}/0.8\right) \tag{65}$$

Conventional boiler fuel use is split between biomass-derived fuels and fossil fuels. The total available biomass is calculated as byproduct fuels (*BYPBSCR_biofuel*). Some of it is used in cogeneration; the remainder of the available biomass (*AvailBiomass*) is assumed to be used as boiler fuel. The amount of steam from this biomass (*BIOSTEAM*) is estimated based on assumed biomass boiler efficiency (0.69).

The steam demand that must be met through fossil-fired boilers is the total non-cogenerated steam (*NonCogSteam*) less the biofueled steam (*BIOSTEAM* or *NonCogFosSteam*). A trial estimate for total fossil fuel for boilers is derived from *NonCogFosSteam* assuming average boiler efficiency across fuels.

Allocating this total to specific fuels in a manner consistent with MECS data is difficult. The MECS data indicate only the total amounts of indirect fuels associated with boilers and cogeneration, so fuel-specific boiler use cannot be computed from MECS data alone. Because fuel use and thermal output data is taken from Form EIA-860, deriving an estimated conventional boiler fuel requirement consistent with MECS requires a calibration step. The model calibrates the fuel volumes to ensure that the sum of the cogeneration fuel and conventional boiler fuel (from Form 860) equals the MECS indirect fuel estimate in the base year.

The derivation of the boiler fuel calibration factor is based on the results of subroutine MecsLess860, which, as its name implies, calculates the difference between total MECS indirect fuels (*BSCbsyr*) and the

cogeneration (or CHP) fuel use from Form 860 (*CHPbsyr*) and stores it in array *BOILBSYR*. A separate calibration is performed for biomass- and fossil-fueled boilers. The calibration factor for fossil fuels is computed as follows for model year 2014:

$$Estimated = NonCogFosSteam / 0.8 \qquad (66)$$

$$Implied = \sum_f BOILBSYR_f \qquad (67)$$

$$CALIBBSYR\_FOS = Implied / Estimated \qquad (68)$$

where

$Estimated$ = Preliminary estimate of fossil fuel use from conventional boilers;

$Implied$ = Conventional boiler fuel use;

$BOILBSYR_f$ = Ratio of MECS and Form 860860 for each boiler fuel f; and

$CALIBBSYR\_FOS$ = Calibration factor for conventional boiler fuel use.

In the projection, the calibration factors for the base year adjust the preliminary estimates to yield the estimated non-cogeneration fossil fuel, as follows:

$$NonCogFosFuel = NonCogFosSteam * BSSHR_f \qquad (69)$$

where

$NonCogFosFuel$ = Non-cogeneration (conventional) fossil fuel use in boilers, calibrated to match MECS when combined with 860 cogeneration data;

$BSSHR_f$ = Boiler fuel shares estimated in subroutine CALBSC; and

$NonCogFosSteam$ is defined above.

Conventional boiler fuel use (*FuelFosSteam_f*) is allocated to fuels based on fuel shares adjusted for price changes since 2014 and fuel-specific efficiencies, as follows:

$$FuelFosSteam_f = \left(NonCogFosFuel \div beff_f\right) * CALIBBSYR\_FOS \qquad (70)$$

where

$beff_f$ = Boiler efficiency by fuel given in Table 5; and

$CALIBBSYR\_FOS$ is defined above.

Table 5. Boiler efficiency by fuel

Fuel	Efficiency (percentage)
Natural gas	78%
Coal	83%
Residual oil	84%
Distillate	80%
Liquefied petroleum gas	76%
Petroleum coke	80%
Other	80%
Biomass	69%

Source: Personal communication with CIBO (Council of Industrial Boiler Owners) 2011

The fossil fuels consumption for non-cogeneration boilers is added to cogeneration fuel consumption to yield total fuel consumption in the boiler, steam, and cogeneration (BSC) component, as follows:

$$ENSQTY_f = CogBoilFuel_f + FosFuelSteam_f \qquad (71)$$

where

$CogBoilFuel_f$ = Fossil fuel consumption for cogeneration by fuel f; and

$FosFuelSteam_f$ = Fossil fuel consumption for conventional boilers by fuel f.

INDTOTAL

The consumption estimates derived in the PA, BSC, and BLD components are combined in INDTOTAL to estimate overall energy consumption for each industry. The consumption estimates include byproduct consumption for each of the main, intermediate, and renewable fuels. Only electricity, natural gas, and steam are included in building consumption. For all fuels except electricity, the following equation is used:

$$QTYMAIN_{f,r,i} = ENPMQTY_{f,r,i} + ENBQTYTOT_{f,r,i} + ENSQTY_{f,r,i} + BYPBSCM_{f,r,i} \qquad (72)$$

where

$QTYMAIN_{f,r,i}$ = Consumption of fuel f and region r;

$ENPMQTY_{f,r,i,,}$ = Consumption of fuel f and region r in the PA component;

$ENBQTYTOT_{f,r,i}$ = Consumption of fuel f and region r for all building end uses;

$ENSQTY_{f,r,i}$ = Consumption of fuel f and region r to generate steam; and

$BYPBSCM_{f,r,i}$ = Byproduct consumption of fuel f and region r to generate electricity from the BSC component.

For modeling purposes, consumption of electricity is defined as purchased electricity only; therefore, electricity generation for own use is removed from the consumption estimate as follows:

$$QTYMAIN_{,elec,r,i} = ENPMQTY_{elec,r,i} + ENBQTYTOT_{elec,r,i} - ELOWN_{r,i} \qquad (73)$$

where

$QTYMAIN_{elec,r},$ =   Consumption of purchased electricity in region r ;

$ENPMQTY_{elec,r}$ =   Consumption of electricity in the PA component in region r;

$ENBQTYTOT_{elec,r}$ =   Consumption of electricity for all building end uses; and

$ELOWN_r$ =   Electricity generated for own use, from subroutine CALGEN.

NATTOTAL

After calculating energy consumption for all four census regions for an industry, NATTOTAL computes a national industry estimate of energy consumption. This subroutine also computes the consumption total over all fuel categories (main, intermediate, and renewable). Total consumption for the entire industrial sector for each main, intermediate, and renewable fuel is computed by accumulating across all industries as follows:

$$TQMAIN_f = \sum_{r=1}^{4} \sum_{i=1}^{INDMAX} QTYMAIN_{f,r,i} \qquad (74)$$

where

$TQMAIN_f$ = Total national consumption for fuel f;

$INDMAX$ = Number of industries;, and

$QTYMAIN_{f,r,i}$ = Consumption of fuel f for census region r and Industry i.

CONTAB

CONTAB reports consumption values for individual industries. National consumption values are reported for each of the fuels used in each particular industry. The procedure for main fuels in the food products industry is calculated as follows[36] (with similar equations used for the other industries):

$$FOODCON_f = \sum_{r=1}^{4} QTYMAIN_{f,r,i=7} \qquad (75)$$

where

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[36]Another subroutine, INDFILLCON, is called from CONTAB to actually fill the FOODCON consumption array.

$FOODCON_f$	=	Total national consumption of fuel f in the food products industry;
$QTYMAIN_{f,r,i=7}$	=	Consumption of fuel f for census region r in the food products industry.

WRBIN

WRBIN writes data for each industry to a binary file. Two different binary files are created. The first contains variables and coefficients that do not change over time but vary over industry or process. The second binary file contains data that vary by projection year.

INDCGN

Subroutine INDCGN calculates aggregate industrial sector cogeneration capacity, generation, and fuel use by summing the results of subroutine CALGEN over the 21 industries. Subroutine INDCGN shares these cogeneration results into two parts: that associated with generation for own use and that used for sales to the grid. The results are copied to the corresponding NEMS global data variables for industrial cogeneration capacity (*CGINDCAP*), generation (*CGINDGEN*), and fuel use (*CGINDQ*), as follows:

$$CGINDCAP_{d,f,grid} = \sum_i^{ind\ max}\left(COGCAP_{d,i,f} * COGGRD_{d,i,f}\right) \tag{76}$$
$$CGINDCAP_{d,f,ownuse} = \sum_i^{ind\ max}\left(COGCAP_{d,i,f} * \left(1 - COGGRD_{d,i,f}\right)\right) \tag{77}$$

$$CGINDGEN_{d,f,grid} = \sum_i^{ind\ max}\left(COGGEN_{d,i,f} * COGGRD_{d,i,f}\right) \tag{78}$$

$$CGINDGEN_{d,f,ownuse} = \sum_i^{ind\ max}\left(COGGEN_{d,i,f} * \left(1 - COGGRD_{d,i,f}\right)\right) \tag{79}$$
$$CGINDQ_{d,f,grid} = \sum_i^{ind\ max}\left(COGELF_{d,i,f} * COGGRD_{d,i,f}\right) \tag{80}$$
$$CGINDQ_{d,f,ownuse} = \sum_i^{ind\ max}\left(COGELF_{d,i,f} * \left(1 - COGGRD_{d,i,f}\right)\right) \tag{81}$$

where

$CGINDCAP_{d,f,u}$	=	Cogeneration capacity by census division d, fuel f, and use $u \in [grid, ownuse]$;
$CGINDGEN_{d,f,u}$	=	Cogeneration generation by census division d, fuel f, and use u;
$CGINDQ_{d,f,u}$	=	Cogeneration fuel use, electricity portion, by census division d, fuel f, and use u;
$COGGRD_{d,i,f}$	=	Share of cogeneration sold to the grid by census division d, industry i, and fuel f;
$COGCAP_{d,i,f}$	=	Cogeneration capacity by census division d, industry i, and fuel f;
$COGGEN_{d,i,f}$	=	Cogeneration generation by census division d, industry i, and fuel f; and

$$COGELF_{d,i,f} \quad = \quad \text{Cogeneration fuel use, electricity portion, by census division } d, \text{ industry } i, \text{ and fuel } f.$$

WEXOG

WEXOG writes calculated industrial quantities to the NEMS exogenous variable array. Before assigning values to the NEMS variables, the model computes total industrial fuel consumption quantities. These values are then calibrated or benchmarked to the SEDS estimates for each data (history) year, and thereafter are calibrated to the STEO projection estimates. The calibration factors are multiplicative for all fuels that have consumption values greater than zero and are additive otherwise.

The equation for total industrial electricity consumption is below. Similar equations are used for all other fuels. Where appropriate, the summands include refinery consumption and oil and natural gas consumption, as follows:[37]

$$BMAIN_f = TQMAIN_f + QELRF \tag{82}$$

where

$BMAIN_f$ = Total (industrial and refinery) consumption of fuel f (electricity);

$TQMAIN_f$ = IDM consumption of fuel f (electricity); and

$QELRF$ = Refinery consumption of fuel f (electricity).

The equation for total industrial natural gas consumption is given as follows:

$$BMAIN_{f,s,o} = TQMAIN_f + QNGRF + CGOGQ_{sg} + CGOGQ_{og} \tag{83}$$

where

$BMAIN_f$ = Consumption of fuel f (natural gas);

$TQMAIN_f$ = Consumption of fuel f (natural gas);

$QNGRF$ = Consumption of natural gas from refining;

$CGOGQ_{sg}$ = Consumption of natural gas from cogeneration of electricity for sales to the grid in enhanced oil recovery sg, input from Oil and Gas Supply Module; and

$CGOGQ_{og}$ = Consumption of natural gas from cogeneration of electricity for own use in enhanced oil recovery og, input from Oil and Gas Supply Module.

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[37] Consumption of electricity and fuels for the production of ethanol is calculated in the Liquid Fuels Market Module and consumption of electricity for the processing of oil shale is calculated in the Oil and Gas Supply Module.

Total industrial consumption for other fuels is calculated similarly.

Regional SEDS benchmark factors are calculated as follows:

$$SEDSBF_{f,d} = \frac{\sum_d SEDS4_{f,d}}{BMAIN_f} \qquad (84)$$

where

$SEDSBF_{f,d}$	=	Current SEDS data year benchmark factors by fuel ;
$SEDS4_{f,d}$	=	Current SEDS data year consumption for census division d, aggregated to the census region level by fuel f; and
$BMAIN_f$	=	Total industrial consumption of fuel f.

SEDS benchmark factors are then multiplied by the total industrial consumption value as follows:

$$BENCH_f = SEDSBF_f * BMAIN_f \qquad (85)$$

where

$BENCH_f$	=	Benchmarked total industrial consumption of fuel f; and

$SEDSBF_f$ and $BMAIN_f$ are defined above.

STEO benchmark factors are calculated as follows:

$$STEOBF_f = \frac{STEO_f}{\sum_f \sum_r BENCH_{f,r}} \qquad (86)$$

where

$STEOBF_f$	=	STEO benchmark factor, which equals each fuel's share of the total SEDS benchmarked industrial consumption, by fuel f (note that these factors are applied post SEDS data years);
$STEO_f$	=	STEO projected industrial consumption by fuel f for each STEO projection year; and
$BENCH_{f,r}$	=	Benchmarked total industrial consumption by fuel.

The STEO factors are applied to the SEDS industrial benchmarked consumption values as follows:

$$FinalBENCH_f = STEOBF_f * BENCH_f \qquad (87)$$

To avoid a break in the series after the last STEO projection year, the STEO benchmark factors are incrementally decreased to one (zero impact) beginning in the first year after the STEO projection year through 2015.

Because most renewable fuel consumption occurs in the paper and wood industries, the consumption shares for renewable fuels depend on the paper and lumber industries, shown as follows:

$$DSRENW_d = \frac{OUTIND_{8,d} + OUTIND_{19,d}}{\sum_{d=1}^{NUM_r}(OUTIND_{8,d} + OUTIND_{19,d})} \tag{88}$$

where

$DSRENW_d$	=	Share of output for in census division d;
$OUTIND_{8,d}$	=	Gross value of output for the paper and allied products industry (i = 8) in census division d;
$OUTIND_{19,d}$	=	Gross value of output for the wood products industry (i = 19) in census division d; and
NUM_r	=	Number of census divisions in census region r.

The benchmark factor for biomass is computed as follows:

$$BENCHFAC_{bm,d} = \frac{BIOFUELS_d}{\sum_{f=2}^{3} DQRENW_{f,d}} \tag{89}$$

where

$BENCHFAC_{bm,d}$	=	Benchmark factor for biomass bm in census division d;
$BIOFUELS_d$	=	Consumption of biofuels in census division d; and
$DQRENW_{f,d}$	=	Consumption of renewable fuel f in census division d.

The renewable fuel consumption estimated above is calculated as follows:

$$DQRENW_{f,r,d} = TQRENW_{f,r} * DSRENW_{f,d} \tag{90}$$

where

$TQRENW_{f,r}$	=	Industrial total consumption of renewable fuel f in census region r; and
$DSRENW_{f,d}$	=	Share of output for renewable fuel f in census division d within region r.

Benchmarked consumption values are then passed into the appropriate variables for reporting to NEMS. The following equation calculates consumption of electricity, with equations for other fuels being similar:

$$QELIN_{elec,d} = BENCH_{elec} * SEDSHR_{elec,d} \tag{91}$$

where

$QELIN_d$	=	Industrial consumption of electricity in census division d;

$BENCH_{elec}$ = Consumption of electricity; and

$SEDSHR_{elec,d}$ = SEDS share of electricity in census division d.

The following two equations represent the consumption of core and non-core natural gas:

$$QGFIN_{ngas,d} = BENCH_{ngas} * SEDSHR_{ngas,d} * \left[\frac{TQMAIN_{cng} + TQMAIN_{fds}}{BMAIN_{ngas}}\right] \qquad (92\,)$$

where

$QGFIN_d$ = Industrial consumption of core natural gas in census division d;

$BENCH_{ngas}$ = Benchmarked consumption of total natural gas;

$SEDSHR_{ngas,d}$ = SEDS share of natural gas in census division d;

$TQMAIN_{cng}$ = Consumption of core natural gas, from Subroutine NATTOTAL;

$TQMAIN_{fds}$ = Consumption of feedstock natural gas, from Subroutine NATTOTAL; and

$BMAIN_{ngas}$ = Total un-benchmarked (calculated) consumption of natural gas.

$$QGIIN_d = QNGIN_{ngas,d} - QGFIN_d \qquad (93\,)$$

where

$QGIIN_d$ = Industrial consumption of non-core natural gas in census division d;

$QNGIN_{ngas,d}$ = Consumption of natural gas in census division d; and

$QGFIN_d$ = Industrial consumption of core natural gas in census division d.

Industrial consumption of biomass is calculated as follows:

$$QBMIN_{f,d} = \left[\sum_{f=2}^{3} DQRENW_{f,d}\right] + \left[\sum_{u=1}^{2} CGOGO_{d,bm,u}\right] + QBMRF_d \qquad (94\,)$$

where

$QBMIN_d$ = Industrial consumption of biomass in census division d;

$DQRENW_{f,d}$ = Consumption of renewable fuel f in census division d;

$CGOGO_{d,bm,u}$ = Consumption of biomass bm from cogeneration of electricity for use in enhanced oil recovery u in census division d; and

$QBMRF_d$ = Biomass consumed by petroleum refining industry in census division d.

Consumption of total renewable fuels is calculated by summing the consumption totals for the individual renewable fuel sources as follows:

$$QTRIN_d = QHOIN_d + QBMIN_d + QGEIN_d + QSTIN_d + QPVIN_d + QWIIN_d + QMSIN_d \quad (95)$$

where

$QTRIN_d$	=	Total industrial consumption of renewable fuels in census division d;
$QHOIN_d$	=	Industrial consumption of hydropower in census division d;
$QBMIN_d$	=	Industrial consumption of biomass in census division d;
$QGEIN_d$	=	Industrial consumption of geothermal in census division d;
$QSTIN_d$	=	Industrial consumption of solar thermal in census division d;
$QPVIN_d$	=	Industrial consumption of photovoltaic in census division d;
$QWIIN_d$	=	Industrial consumption of wind in census division d; and
$QMSIN_d$	=	Industrial consumption of municipal solid waste in census division d.

RDBIN

RDBIN is called by the main industrial subroutine ISEAM on model runs after the first model year. This subroutine reads the previous year's data from the binary files. The previous year's values are assigned to lagged variables for price, value of output, and employment. The previous year's UECs, TPC coefficients, price elasticities, and intercepts are read into the variables for initial UEC, TPC, price elasticity, and intercept. Process-specific data are read into either a lagged variable or an initial estimate variable. Three cumulative variables are calculated in this subroutine for future use. A cumulative output variable, a cumulative UEC, and a cumulative production variable are computed for each fuel and process step.

MODCAL

MODCAL performs like the main industrial subroutine ISEAM in all years after the first model year. In subsequent years, no data need to be read from the input files; however, UECs and TPC coefficients must be adjusted to reflect the new model year, whereas the first model year uses only initial estimates of these values. MODCAL calls the following subroutines: CALPROD, CALCSC, CALPRC, CALPATOT, CALBYPROD, CEMENT_INDUSTRY, LIME_INDUSTRY, CALBTOT, CALGEN, CALBSC, CALSTOT, INDTOTAL, NATTOTAL, and CONTAB. Similar to the functioning of ISEAM, the subroutines NATTOTAL and CONTAB are called only after the last region for an industry has been processed.

CALPROD

CALPROD determines the throughput for production flows for the process and assembly component for industries that are not process flow industries. Existing old and middle vintage production is reduced by

applying a retirement rate of capital. The retirement rate is posited to be a positive function of energy prices., as follows:

$$RetirePriceFactor = \frac{Pricerat_y^{RetireBeta}}{\left(1 + Pricerat_y^{RetireBeta}\right)} \qquad (96)$$

$$RetireRate_s = 2 * RetirePriceFactor * ProdRetr_s \qquad (97)$$

$$PRODCUR_{old,s,y} = \left(PRODCUR_{old,s,y-1} + IDLCAP_{old,s,y-1}\right) * \left(1 - RetireRate_{s,y-1}\right) \qquad (98)$$

where

$Pricerat_y$	=	is defined on page 47;
$RetireBeta$	=	Parameter of logistic function, currently specified as 2 for retirements;
$RetirePriceFactor$	=	TPC price factor, ranging from 0 (no price effect) to 2 for retirements;
$RetireRate_s$	=	Retirement rate, after accounting for energy price increases, for step s; and
$ProdRetr_s$	=	Default retirement rate for step s.

where

$PRODCUR_{old,s,y}$	= Existing production for process step s for old vintage and year y;
$IDLCAP_{old,s}$	= Idle production at process step s for old vintage; and year y

Total production throughput for the industry is calculated. If the initial UEC is in physical units, the value of output for the current year is multiplied by the fixed ratio of physical units to value of output calculated in the first model year, as follows:

$$PRODX = PHDRAT * PRODVX \qquad (99)$$

where

$PRODX$	=	Value of output in physical units in base year;
$PHDRAT$	=	Ratio of physical units to value of output (by industry but not region); in base year and

$PRODVX$ =   Output in dollars in the base year.

If the initial UEC is in dollar units, then the current year's value of output is used to determine total production throughput. Total production throughput is calculated by determining new capacity requirements at each process step so as to meet final demand changes and replace retired capacity. This is complicated because retirement rates of some steps differ, as do the process flow rates of old and new capacity. In addition, several process steps may jointly provide output for one or more downsteps. The solution to the problem is simplified by formulating the process flow relationships as input-output coefficients as described in the Leontief Input-Output Model (as described in Chiang, *Fundamental Methods of Mathematical Economics*, pp. 123-131). In this model, the output of a process step can either be a final demand or used as input to another process step. The objective is to determine the mix of old and new productive capacity at each process step such that all final demands are met. In this case, the final demand is the industry output.

The following definitions are provided to illustrate the problem:

A = Input/output coefficient matrix with final demand as the first column and the production steps as the other columns. The coefficients are the values in the *PRODFLOW* array, placed in the array according to the *IPASTP* step definitions;

I = Identity array;

D = Final demand vector, but only the first element in nonzero (D_1 is equivalent to $PRODX$); and

X = Vector of productive capacity needed to meet the final demand, based on **A** and **D** (**X** is equivalent to $PRODCUR$).

The input-output model is written as follows:

$$(I - A_y) * X_y = d_y \qquad\qquad (\,100\,)$$

X is obtained by pre-multiplying both sides by the inverse of (**I-A**):

$$X_y = (I - A_y) * d_y \qquad\qquad (\,101\,)$$

Since the **A** coefficients for old and new capacity differ, there are two such arrays: **A**_{old} and **A**_{new}. The corresponding technology matrices are (**I** - **A**_{old}) and (**I** - **A**_{new,y})

Likewise, **X**_{old} and **X**_{new,y} are distinguished to account for old and new productive capacity. However, to incorporate the retirement calculation, the base year productive capacity will be referred to as **X**_{old} and the portion of that capacity that survives to a given year is called **X**_{surv,y}. The portion that is retired is called **X**_{ret}. Therefore, total productive capacity (**X**_{tot}) is given by the following:

$$\mathbf{X_{tot,y}} = \mathbf{X_{surv,y}} + \mathbf{X_{new,y}} \qquad\qquad (102\,)$$

Or

$$\mathbf{X_{tot,y}} = \mathbf{X_{old}} - \mathbf{X_{ret,y}} + \mathbf{X_{new,y}} \qquad\qquad\qquad (103\,)$$

X$_{old}$ is defined in the base year as follows:

$$(\mathbf{I} - \mathbf{A_{old}}) * \mathbf{X_{old}} = \mathbf{d}_{2014} \tag{104}$$

$$\mathbf{X_{old}} = (\mathbf{I} - \mathbf{A_{old}})^{-1} * \mathbf{d}_{2014} \tag{105}$$

X$_{new,y}$ is defined as the cumulative capacity additions in year y since the base year.

A set of retirement rates, *R*, is defined for each producing step. The final demand step need not have a designated retirement rate. Retired **c**apacity is given by the following:

$$\mathbf{X_{ret}} = \mathbf{X_{old}} * (\mathbf{1} - \mathbf{R})^{(y-2014)} \tag{106}$$

$$\mathbf{X_{surv}} = \mathbf{X_{old}} - \mathbf{X_{ret}} \tag{107}$$

The final demand that can be met by the surviving capacity is given by the following:

$$\mathbf{d}_{orig,y} = (\mathbf{I} - \mathbf{A}_{old}) * \mathbf{X_{surv,y}} \tag{108}$$

The remaining demand must be met by new capacity, such that the following condition holds:

$$(\mathbf{I} - \mathbf{A}_{old}) * \mathbf{X}_{surv,y} + (\mathbf{I} - \mathbf{A}_{new}) * \mathbf{X}_{new,y} = \mathbf{d}_y \tag{109}$$

where **X$_{new,year}$** is the cumulative additions to productive capacity since the base year. **X$_{new,year}$** can be determined by solving the following system:

$$(\mathbf{I} - \mathbf{A})_{new,y} * \mathbf{X}_{new,y} = \mathbf{d}_y - (\mathbf{I} - \mathbf{A}_{old}) * \mathbf{X}_{surv,year} \tag{110}$$

Therefore, the following equation holds:

$$\mathbf{X}_{new,y} = (\mathbf{I} - \mathbf{A}_{new})^{-1} * \left(\mathbf{d}_{year} - (\mathbf{I} - \mathbf{A}_{old}) * \mathbf{X}_{surv,y} \right) \tag{111}$$

The last equation is used to implement the approach in the model. The solution is found by calling a matrix inversion routine to determine (**I - A$_{new}$**)$^{-1}$, followed by calls to intrinsic matrix multiplication functions to solve for **X$_{new}$**. As a result, the amount of actual code to implement this approach is minimal.

CALBYPROD

The IDM is run assuming that all byproduct fuels are consumed before the purchasing of any fuels. The CALBYPROD subroutine calculates the energy savings or the location on the technology possibility curve (TPC) based on the current year's industry production and the previous year's industry production for each process step, fuel, and vintage resulting from byproduct fuel consumption. The TPC for biomass byproducts is assumed to be a positive function of energy prices. For all other industries that do not include iron and steel and pulp and paper, the UEC remains unchanged. The iron and steel and pulp and paper industries now do not use this subroutine since submodule CHP uses specific code.

$$TPCRate_{v,f.s,y} = 2*TPCPriceFactor_y * BYPCSC_{v,f,s} \tag{112}$$

where

$TPCRate_{v,f,s,y}$ =   is calculated on page 47;

$TPCPriceFactor_y$ =   is calculated in page 47;

$BYPCSC_{v,f,s}$ =   Initial TPC for vintage v, fuel f, and step s.

CALBYPROD calculates the rate of byproduct energy produced for each process step, fuel, and vintage as shown in the following equation. This value is based on the previous year's rate of production and the current energy savings for each vintage:

$$BYPINT_{v,f,s} = \left(BYPINTLag_{v,f,s}\right)^{TPCRate_v} \tag{113}$$

where

$BYPINT_{v,f,s}$ =   Rate of byproduct energy production (or UEC) for byproduct fuel f at process step s for vintage v;

$BYPINTLag_{v,f,s}$ =   Lagged rate of byproduct energy production for byproduct fuel f at process step s for vintage v; and

$TPCRate_v$ =   TPC multiplier on TPC rate due to energy price increases for vintage, v, calculated on page 47.

The UEC for middle vintage is a weighted average (by production) of the previous year's energy savings for new vintage and the previous year's energy savings for middle vintage, as shown by the following:

$$BYPINT_{mid,f,s} = \left[\frac{\left(PRODLag_{mid,f,s} * BYPINTLag_{mid,f,s}\right)}{\left(PRODLag_{mid,s} + PRODLag_{new,s}\right)} + \frac{\left(PRODLag_{new,s} * BYPINTLag_{new,f,s}\right)}{\left(PRODLag_{mid,s} + PRODLag_{new,s}\right)} \right]^{TPCRate_{mid}} \tag{114}$$

where

$PRODLag_{new,s}$ = Previous year's production from new vintage capacity at process step s;

$BYPINTLag_{new,f,s}$ = Lagged rate of byproduct energy production for byproduct fuel f at process step s for new vintage;

$PRODLag_{mid,s}$ = Previous year's production from middle vintage capacity at process step s;

$BYPINTLag_{mid,f,s}$ = Lagged rate of byproduct energy production for byproduct fuel f at process step s for middle vintage; and

$TPCRate_{mid}$ =TPC multiplier on TPC rate due to energy price increases for middle vintage; calculation is shown on page 47.

The rate of byproduct fuel production is used to calculate the quantity of byproduct energy produced by multiplying total production at the process step by the production rate, as shown in the following:

$$BYPQTY_{v,f,s} = PRODCUR_{v,s} * BYPINT_{v,f,s} \quad (115)$$

where

$BYPQTY_{v,f,s}$ = Byproduct energy production for byproduct fuel f at process step s for vintage v;

$PRODCUR_{v,s}$ = Production at process step s for vintage v; and

$BYPINT_{v,f,s}$ = Rate of byproduct energy production for byproduct fuel f at process step s for vintage v.

Note that $PRODCUR_{v,s}$ is production by a vintage at a step and is not fuel-specific. The rate of byproduct fuel production is then converted from millions of Btu to trillions of Btu. Byproduct fuel production is subdivided into three categories: main fuels, intermediate fuels, and renewable fuels.

Byproduct production for each group of fuels is determined by summing byproduct production over the individual process steps for each fuel and vintage as shown below for main byproduct fuels. The equations for intermediate and renewable fuels are similar, as follows:

$$\text{ENBYM}_{f,v,s} = \sum_{s=1}^{MPASTP} \text{BYPQTY}_{f,v,,s} \quad (116)$$

where

$ENBYM_{f,v,s}$ = Byproduct energy production for main byproduct fuel f for vintage v and process step s;

$MPASTP$ = Number of process steps; and

$BYPQTY_{f,v,s}$ = Byproduct energy production for byproduct fuel f for vintage v at process step s.

CALCSC

CALCSC computes UEC for all industries. The current UECs for the old and new vintages are calculated as the product of the previous year's UEC and a factor that reflects the assumed rate of intensity decline over time and the impact of energy price changes on the assumed decline rate.

For all industries except the process flow industries,[38] the IDM capital stock is grouped into three vintages: old, middle, and new. The old vintage consists of capital in production in 2014 and is assumed to retire at a fixed rate each year. Middle vintage capital is that which is added from 2014 through the year *Year*-1, where *Year* is the current projection year. New capital is added for the projection years when existing production is less than the output projected by the MAM. Capital stock added during the projection period is retired in subsequent years at the same rate as the pre-2014 capital stock.

The annual UEC for the old and new vintage is calculated as the product of the previous year's UEC and a factor that reflects the assumed rate of intensity decline over time and the impact of energy price changes on the assumed decline rate, given as follows:

$$Enpint_{v,f,s,y} = EnpintLag_{v,f,s,y} * (1 + TPCRate_v) \qquad (117)$$

where

$Enpint_{v,f,s}$	=	Unit energy consumption of fuel f at process step s for vintage v;
$EnpintLag_{v,f,s}$	=	Previous year's energy consumption of fuel f at process step s for vintage v; and
$TPCRate_v$	=	Energy intensity decline rate for vintage v after accounting for the impact of increased energy prices.

The values for TPCRate$_v$ are calculated using the following relationships if the fuel price is higher than it was in 2014. Otherwise, the default value for the intensity decline rate (BCSC$_{v, f, s}$) is used.

$$Pricerat_y \quad = \quad \max\left(1, \frac{AvgPrice_y}{AvgPrice_{2014}}\right) \qquad (118)$$

$$TPCPriceFactor_y = \frac{Pricerat_y^{TPCBeta}}{1 + Pricerat_y^{TPCBeta}} \qquad (119)$$

$$TPCRate_{v,f,s,y} = 2 * TPCPriceFactor_y * BCSC_{v,f,s} \qquad (120)$$

where

$Pricerat_y =$ Ratio of current year average industrial energy price to 2014 price;

$TPCBeta =$ Parameter of logistic function, currently specified as 4;

$TPCPriceFactor_y =$ TPC price factor, ranging from 0 (no price effect) to 2 for ENPINT;

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[38] The process flow industries are cement and lime, aluminum, glass, iron and steel, and pulp and paper.

$$TPCRate_{v,f,s,y} = \quad \text{Intensity for capital of vintage } v, \text{ fuel } f, \text{ step } s, \text{ and year } y \text{ after accounting for changes due to energy price changes for vintage } v; \text{ and}$$

$$BCSC_{v,f,s} = \quad \text{Default intensity rate for old and new vintage } v \text{ for each fuel } f \text{ and step } s.$$

The UEC for middle vintage is calculated as the ratio of cumulative UEC to cumulative production for all process steps and industries, that is, the weighted average UEC, as follows:

$$ENPINT_{mid,f,s} = \frac{SUMPINT_{f,s}}{CUMPROD_{new,s}} \qquad (121\,)$$

where

$ENPINT_{mid,f,s,y}$ =   UEC of process step s for fuel f at middle vintage mid;

$SUMPINT_{f,s}$ =   Cumulative UEC of process step s for fuel f; and

$CUMPROD_{new,s}$ =   Cumulative production at process step s for new vintage.

CALBSC

This subroutine revises boiler fuel shares are revised each year based on changes in fuel prices since the base year. The fuel sharing is calculated using a logit formulation. The fuel shares apply only to conventional boiler fuel use. Cogeneration fuel shares are assumed to be constant and are based on data from Form EIA-860. Base year boiler fuel use is obtained by subtracting cogeneration fuel use from total MECS indirect fuels (this calculation is done in subroutine MECSLESS860. Waste and byproduct fuels are excluded from the logit calculation because they are assumed to be consumed first. The boiler fuel sharing equation for each industry is as follows:

$$ShareFuel_{i,f,y} = \frac{\left(P_{f,y}^{\propto_f} \beta_f\right)}{\sum_{f=1}^{3} P_{f,y}^{\propto_f} \beta_f} \qquad (122\,)$$

where

$ShareFuel_f$ = Boiler fuel share for industry i and fuel f in year y;

P_f =   Fuel price relative to the 2014 price for fuel f with fuel premium index applied [39]; and

$\propto_f$ = Sensitivity parameter for fuel f, default value is -2.0;

β_f = efficiency for boiler fuel fired by fuel f.

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[39] NESCAUM, Applicability and feasibility of NOx, SO2, and PM Emissions Control Technologies for Industrial, Commercial, and Institutional (ICI) Boilers, January 2009.

Table 6. Index price premiums for boiler fuel share selection

	Coal	Oil	Natural gas
Cost premium (index)	1.25	1.10	1.00

The fuels (f) are limited to coal, petroleum, and natural gas because these are the only fuels used in substantial quantities in industrial boilers. Base year boiler shares for individual petroleum products are calculated explicitly to obtain exact estimates of these fuel shares from the aggregate petroleum fuel share calculation. The byproduct fuels are consumed before the quantity of purchased fuels as explained in the WEXOG section on page 71.

Non-manufacturing subroutines

AGRICULTURE INDUSTRY: Subroutine AGTPC

The AGTPC subroutine calculates the consumption of energy in the agriculture industries by further subdividing consumption in each sub-industry based on the equipment in which the energy is used: off-road vehicles, which are trucks, tractors, and other specialty vehicles; buildings, which require lighting and temperature control; and other equipment, which covers a variety of both common (for example, pumps) and specialty (for example, cotton gins) equipment used in all the various types of agricultural production.

Vehicle intensity is calculated as a weighted average using the existing stock of light-, medium-, and heavy-duty trucks. The miles per gallon (mpg) measured by fuel from the Transportation Sector Module is indexed to decline over time. The TPC for agricultural vehicles is therefore estimated in the model as follows:

$$VEH\_Index_{f,y} = \left(\frac{Trk\_Intens_{f,y}}{Trk\_Intens_{f,y-1}} \right) - 1 \qquad (123)$$

$$Trk\_Intens_{f,y} = \frac{1}{\sum_s TFR\_TRK\_FAS\_T_{s,f,y}} \sum_s \frac{TFR\_TRK\_FAS\_T_{s,f,y}}{TFR\_FTMPG_{s,f,y}} \qquad (124)$$

where

$VEH\_Index_{f,y}$ =Index used to calculate sub-industry TPC for vehicles for fuel f in year y;

$Trk\_Intens_{f,y}$ = Average truck energy intensity for fuel f in year y;

$TFR\_TRK\_FAS\_T_{s,f,y}$ = Existing truck stock for fuel f in year y for truck size s; and

$TFR\_FTMPG_{s,f,y}$ = Truck mpg for truck size s for fuel f in year y for truck size s.

Building energy intensity is calculated using an index of heating, lighting, and building shells retrieved from the Commercial Demand Module (CDM) for warehouses because this building type is most similar to the types of buildings used in agricultural production. The shares for these three energy users are based on data analysis commissioned by EIA[40] and shown in Table 7. The TPC for agricultural buildings is estimated in the model as follows:

$$BLD\_Index_{r,1,y} = \left(\frac{WHSE\_HeatIndex_{r,f,y}}{WHSE\_HeatIndex_{r,f,y-1}} \right) - 1 \qquad (125)$$

$$BLD\_Index_{r,2,y} = \left(\frac{WHSE\_LightIndex_{r,f,y}}{WHSE\_LightIndex_{r,f,y-1}} \right) - 1 \qquad (126)$$

$$BLD\_Index_{r,3,y} = \left(\frac{WHSE\_ShellIndex_{r,f,y}}{WHSE\_ShellIndex_{r,f,y-1}} \right) - 1 \qquad (127)$$

where

$BLD\_Index_{r,k,y}$ =   =   Index, before weighting for heating equipment (k=1), lighting equipment (k=2) or building shells (k=3), used to calculate sub-industry TPC for buildings for region r in year y;

$WHSE\_HeatIndex_{r,f,y}$ =   Composite of warehouse energy consumption in heating equipment retrieved from the Commercial Demand Module in region r for fuel f in year y;

$WHSE\_LightIndex_{r,f,y}$ =   Composite of warehouse energy consumption in lighting equipment retrieved from the Commercial Demand Module in region r for fuel f in year y; and

$WHSE\_ShellIndex_{r,f,y}$ =   Composite of warehouse energy consumption in building shells retrieved from the Commercial Demand Module in region r for fuel f in year y.

Irrigation intensity is computed much the same way as the building intensity, relying on

$WHSE\_VentIndex_{r,f,y}$ instead, as follows:

$$IRR\_Index_{r,f,y} = \left(\frac{WHSE\_VentIndex_{r,f,y}}{WHSE\_VentIndex_{r,f,y-1}} \right) - 1 \qquad (128)$$

     where

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[40] SRA International, Report on the Analysis and Modeling Approach to Characterize and Estimate Fuel Use by End-Use Applications in the Agriculture and Construction Industries, unpublished report prepared for the U.S. Energy Information Administration, March 2011.

$WHSE\_VentIndex_{r,f,y}$ = Composite of warehouse energy consumption in building vents retrieved from the Commercial Demand Module in census region r for fuel f in year y.

Table 7. Building weights for technology possibility curve index by fuel

Equipment type	Heating	Lighting	Shell
Electricity	0.25	0.25	0.50
Natural gas	0.25	0.00	0.75
Distillate	0.25	0.00	0.75
Natural gas liquids	0.25	0.00	0.75
Motor gasoline	0.25	0.00	0.75

Source: Commercial Demand Module Documentation

Other equipment is directly indexed to other warehouse equipment using a fourth composite retrieved from the CDM.[41]

CONSTRUCTION INDUSTRY: Subroutine CONTPC

Although construction is represented as one sector, there are several subsectors within construction that have different energy consumption characteristics. Therefore, in order to calculate aggregate UEC, the Construction sector is divided into three functional groups, as defined by NAICS codes 236, 237, and 238: Buildings, Civil Engineering, and Trade. Energy use is allocated within those groups, by fuel type and region, based on Census estimates of expenditures (apportioned by the number of employees) and regional weighted average fuel prices. The following fuel expenditures are obtained from the 2012 Economic Census for the construction industry:[42]

Table 8. Total cost of selected power, fuels, and lubricants, 2012 (million U.S. dollars)

North American Industrial Classification System code	Definition	Purchased electricity	Natural gas plus liquefied petroleum gas	Gasoline and distillate	Other
23	Construction	2,811.3	0.9	19,755.6	0.8

U.S. Census Bureau, Economic Census 2012 data, Construction
https://www.census.gov/data/datasets/2012/econ/census/2012-construction.html

Because gasoline and distillate (or diesel fuel) expenditures are combined in the Economic Census, it is necessary to split this figure into its components. This process is done using SEDS data to construct consumption-weighted estimates of regional shares of gasoline and distillate sales for industrial and commercial consumers.

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[41]Details of the three warehouse energy consumption variables can be found in U.S. Energy Information Administration, Documentation of the Commercial Demand Module (CDM), DOE/EIA-M066(2013), Washington, DC, July 2011, pg. 16-39.
[42]https://www.census.gov/data/datasets/2012/econ/census/2012-construction.html.

Table 9. Gasoline/distillate volume allocation

Region	Gasoline	Distillate
1	12%	88%
2	21%	79%
3	20%	80%
4	17%	83%

Source: State Energy Data System

The regional shares of employees by functional group are derived from the 2006 Census of Employment and Wages.[43]

Table 10. Regional share of employees, by functional group

Census region	Buildings	Civil engineering	Trade
1	15%	11%	15%
2	19%	18%	20%
3	39%	48%	38%
4	27%	23%	28%
Total	100%	100%	100%

Source: U.S. Bureau of Labor Statistics, 2006 Census of Employment and Wages.

These factors inform the allocation of UECs by region, functional group and fuel, displayed in the following table. The current weighting structure is static and is based on the 2007 Economic Census allocation of fuel costs for the functional groups (buildings, civil engineering, and trade), SEDS regional allocation of fuel consumption, and regional employment data. These UEC allocation factors are represented in the code as WEIGHT_CON(r, g, f), where the indexes represent the region, functional group (buildings, civil engineering, trade), and fuel type, respectively.

Table 11. Construction unit energy consumption weights by region: variable weight_con

Functional group and census region	Electricity	Natural gas	Distillate	Other	Gasoline
Region 1					
Buildings	35.4%	24.3%	18.5%	11.0%	18.5%
Civil engineering	20.1%	36.3%	18.8%	34.6%	18.8%
Trade	44.5%	39.4%	62.8%	54.5%	62.8%
Region 2					
Buildings	33.3%	22.1%	17.4%	10.0%	17.4%
Civil engineering	23.5%	40.9%	21.8%	39.0%	21.8%
Trade	43.2%	36.9%	60.8%	51.0%	60.8%
Region 3					

[43]Bureau of Labor Statistics, 2006 Census of Employment and Wages, available at https://www.bls.gov/cew/publications/employment-and-wages-annual-averages/2006/home.htm

Functional group and census region	Electricity	Natural gas	Distillate	Other	Gasoline
Buildings	31.7%	19.9%	16.7%	9.1%	16.7%
Civil engineering	29.3%	48.4%	27.6%	46.7%	27.6%
Trade	39.0%	31.7%	55.7%	44.2%	55.7%
Region 4					
Buildings	33.5%	22.5%	17.3%	10.1%	17.3%
Civil engineering	22.1%	39.0%	20.5%	37.0%	20.5%
Trade	44.4%	38.5%	62.2%	52.9%	62.2%

Sources: 2012 Economic Census, Construction Series; State Energy Data System

The energy demanded for any given fuel is dependent on the value of output in the construction sector, as follows:

$$Q_{r,f,y} = CONSTR_{r,y} * UEC_{r,f,y} \qquad\qquad (129)$$

$$UEC_{r,f,y} = UEC_{r,f,y-1} * (1 + TPC_{f,y}) \qquad\qquad (130)$$

where

$Q_{r,f,y}$ =   quantity demanded in census region r of fuel f for year y; and

$CONSTR_{r,y}$ =   Construction shipments from the MAM for census region *r* and year *y.*

The UEC for each of the four census regions is established for a specific base year (currently 2014) and is calculated using data from the 2012 Census of Employment & Wages, as well as MECS and SEDS. Calculations in years subsequent to the base year recalculate the UECs using a constant factor, the TPC, which reflects an assumed improvement in energy intensity (by fuel *f)* over time (from year *y-1* to year *y*):

The TPC, formerly held constant and exogenously supplied to the model, is now calculated through changes in various indexes of energy intensity, obtained from other NEMS modules.

The following sections describe the drivers that have a dynamic influence on the TPC, reflecting improvements in technology and energy intensity, and applying them to the construction sector. This process has been done by dividing construction energy demand into two categories, Vehicles and Other Equipment, and by looking to the other modules for suitable variables that would guide energy use. In addition, the use of asphalt as a process input requires the use of a measure of economic activity from the MAM, that is, state and local highway investments (changes in which may affect the demand for this product).

Factor indexes for vehicles and equipment

As in the AGTPC subroutine, energy consumption is calculated in the agriculture industries by further subdividing consumption in each sub-industry based on shares of equipment use: off-road vehicles, which are trucks, tractors, and other specialty vehicles; buildings, which require lighting and temperature control; and other equipment, which covers a variety of both common (for example, pumps) and specialty (for example, cotton gins) equipment used in all the various types of agricultural production.

Vehicle energy intensity

The freight truck model generates (at the national level) fuel economy estimates for three classes of truck: medium, medium-heavy, and heavy. The vehicle component of the TPC trends is based on stock-weighted average fuel economy estimates of the truck population, attributed to the three functional groups as follows:

Table 12. Functional groups and vehicles

Function	Functional group	Truck size classes
1	Buildings	Medium, medium-heavy, and heavy
2	Civil engineering	Heavy
3	Trade	Medium and medium-heavy

Source: Transportation Demand Module

Energy intensity of vehicles is defined and calculated using the same method as in the *AGTPC* subroutine (see calculations on page 83).

For each fuel, year, and functional group, marginal change in energy intensity is the following:

$$VEH\_Index\_SC_{f,y,g} = \left(\frac{Trk\_Intens\_SC_{f,y,g}}{Trk\_Intens\_SC_{f,y-1,g}} \right) - 1.0 \qquad (131)$$

This is converted into a weighted vehicle index (weighted over the three functional groups), using the regional UEC weights presented in Table 11:

$$Wtd\_Veh\_Index_{r,f,y} = \sum_{g=1}^{3} VEH\_Index\_SC_{f,y} * Weight\_Con_{r,f,g} \qquad (132)$$

Other Equipment Index

The impact of Other Equipment is determined using proxy measures derived from the CDM and is defined and calculated similar to the AGTPC subroutine as shown on page 83. These measures are based on the weighted average efficiency of Heating, Lighting, and Ventilation services provided to the

Warehouse building type only (type 10 in the CDM). The variable $WHSE\_Index_{r,y,f,s}$ is calculated for heating, lighting, and ventilation (s=1, s=2, s=3 respectively) and passed from the IDM from the CDM.

These figures are converted to elements of a new variable, EQP_Index, which represents each component's fractional improvement from the previous year, as follows:

$$EQP\_Index_{r,y,f,s} = \left(\frac{WHSE\_Index_{r,y,f,s}}{WHSE\_Index_{r,y-1,f,s}} \right) - 1.0 \qquad (133)$$

The collective weighted equipment index is then calculated, based on the contribution each service makes to the consumption of the particular fuel in equation, as follows:

$$Wt\_Eqp\_Index_{r,y,f} = \sum_{g} \sum_{s=1}^{3} EQP\_Index_{r,y,f,s} * Weight\_Con_{r,f,g} * CON\_Proxy\_Wt_{f,s} \qquad (134)$$

The weights of these contributions are provided in the following table. It should be noted that only electricity demand contains contributions from the lighting and ventilation indexes.

Table 13. Fuel use weights for buildings

CON_Proxy_Wt	Heat	Light	Vent
Electricity	20%	20%	60%
Natural gas	100%	0%	0%
Distillate	100%	0%	0%
Natural gas liquids	100%	0%	0%
Gasoline	100%	0%	0%

Source: Commercial Demand Module

Factor index for road investment

One additional index is necessary for the construction industry for asphalt and road oil consumption. Asphalt is a process input and is considered to be more closely linked to the MAM's estimate of state and local highway expenditures. Accordingly, this approach considers the annual growth in highway spending as a share of total construction expenditures, weighted by the vehicle energy intensity index to moderate the overall impact on the TPC. The highway index is represented as follows:

$$GI\_Hwy\_Index_{r,y} = \left(\frac{GI\_Hwy\_Invest_{r,y}}{GI\_Hwy\_Invest_{2011}} \right) * 0.008 \qquad (135)$$

where

$GI\_Hwy\_Invest_{r,y}$ =   State and local highway investment for region r and year y from the MAM (mc_gslgisnhwyr); and

0.008 represents the average annual growth in construction expenditures by year y.

TPC calculation

The TPC for each region r and fuel type f is then calculated. For all energy sources except asphalt, the following calculation applies:

$$TPC_{r,\text{Veh,Eqp},f,y} =$$

$$Wt\_VEH\_Index_{r,y,f} * CON\_Equip\_Wt_{Veh,f} + Wt\_EQP\_Index_{r,y,f} * CON\_Equip\_Wt_{Eqp,f} \quad (\,136\,)$$

where

$$TPC_{r,\text{Veh,Eqp},f,y} \qquad = \quad$$ the relative contribution to the total TPC from vehicles Veh, Other Equipment Eqp, and fuel f as shown in the following table.

Table 14. Relative contribution to total technology possibility curve, vehicles, and other equipment

CON_Equip_Wt	Electricity	Natural gas	Distillate	Other	Gasoline
Vehicles	0.0%	20.0%	50.0%	0.0%	25.0%
Other equipment	100.0%	80.0%	50.0%	100.0%	75.0%

Source: Transportation Demand Module

At present, these allocations are based on analyst judgment, and are used to influence the rate of energy intensity improvement within a fuel type.

For asphalt, the TPC is calculated differently, weighing both asphalt and vehicle consumption, as follows:

$$TPC_{r,y,f} = 0.3 * GI\_Hwy\_Index_{r,y} + 0.7 * Wt\_VEH\_Index_{r,y,f} \qquad (\,137\,)$$

where the vehicle index corresponds to that for diesel-fueled trucks. Finally, for every sector and fuel (including the manufacturing sectors), the baseline TPC is also subject to adjustment by increasing fuel prices using the following formulation, as follows:

$$TPC_{f,y} = TPC_{f,y} * \frac{2 * \left(Price_{f,y} \middle/ Price_{f,BaseYr} \right)^{\beta}}{1 + \left(Price_{f,y} \middle/ Price_{f,BaseYr} \right)^{\beta}} \qquad (\,138\,)$$

where the logit coefficient, β, is set in the IDM code to 4.0.

COAL INDUSTRY

The COALTPC subroutine calculates the consumption of energy in the coal mining industry by further subdividing consumption in each sub-industry based on the equipment in which the energy is used: off-

road vehicles, which are trucks, tractors, and other specialty vehicles; various equipment, which encompasses lighting, heating, and ventilation; and grinding equipment.

The most significant determinant of energy use in the coal mining sector is the distinction between underground and surface mining, and thus aggregate production values of underground vs. surface are obtained from the Coal Market Model (CMM) for use in COALTPC.

The amount of fuel (f) demanded by the Coal Mining industry in year (y) is calculated as follows:

$$Q_{f,y} = COALMN_y * UEC_{f,y} \qquad\qquad (139)$$

where COALMN represents the value of coal mining output, supplied by the MAM.

The IDM calculates this quantity for each of the four census regions. The UEC changes from year to year according to the value of the TPC, as follows:

$$UEC_{f,y} = UEC_{f,y-1} * \left(1 + TPC_{f,y}\right) \qquad\qquad (140)$$

where the TPC indicates the marginal change in energy intensity from the previous year.

The TPC is calculated as the weighted average of three indexes representing the marginal change in three factors: equipment efficiency, the share of underground mining, and labor productivity. These indexes are described in detail below.

Factor indexes
Equipment

Heating, Lighting, and Ventilation

The weighted equipment index depends on the fuel in question and is determined using proxy measures derived from the CDM, the Transportation Demand Module (TDM), and results of the Cement model in the IDM.

From the CDM, measures are based on the weighted average efficiency of Heating, Lighting, and Ventilation services provided to the Warehouse building type (type 10 in the CDM). Definitions and calculations are the same as in the AGTPC subroutine on page 83.

Vehicle Energy Intensity

From the TDM, the freight truck model generates (at the national level) fuel economy estimates for three classes of truck: medium, medium-heavy, and heavy. The contribution to the TPC is based on stock-weighted average fuel economy estimates of the truck population. The average energy intensity is the inverse of the average fuel economy and the marginal change in vehicle energy intensity is defined and computed by fuel (f) and year(y) exactly as in AGTPC subroutine on page 83.

Grinding Equipment

From the results of the cement submodule, the average efficiency of raw grinding equipment is extracted to use as a proxy for changes in the energy intensity of mining equipment. This factor is only applied to the TPC for electricity, as follows:

$$Raw\_Grind\_Eff_y = \frac{\sum_{Tech} Elec\_Use\_Rpt_{Tech,y}}{\sum_{Tech} Tot\_ProdG_{Tech,y}} \qquad (141)$$

where

$Elec\_Use\_Rpt_{Tech,y}$ = Reported electricity consumption for cement grinding, by grinder technology $Tech$ and year y; and

$Tot\_ProdG_{Tech,y}$ = Total grinding output, by grinder $Tech$ and year y.

The weighted equipment index is then calculated. For Electricity, the calculation is as follows:

$$Wt\_EQP\_Index_{f,y} = \left[\frac{Raw\_Grind\_Eff_y}{Raw\_Grind\_Eff_{y-1}} - 1.0 \right] * Elec\_Weight_{Grind}$$

$$+ \left[\frac{WHSE\_LightIndex_y}{WHSE\_LightIndex_{y-1}} - 1.0 \right] * Elec\_Weight_{Light}$$

$$+ \left[\frac{WHSE\_VentIndex_y}{WHSE\_VentIndex_{y-1}} - 1.0 \right] * Elec\_Weight_{Vent} \qquad (142)$$

For other fuels, the calculation is as follows:

$$Wt\_EQP\_Index_{f,y}$$

$$= \left[\frac{WHSE\_HeatIndex_{f,y}}{WHSE\_HeatIndex_{f,y-1}} - 1.0 \right] * NonEl\_Weight_{Heat,f}$$

$$+ VEH\_Index_{f,y} * NonEl\_Weight_{Vehicle,f} \qquad (143)$$

where the various weighting factors are input from an exogenous data file.

Table 15. Energy weights for mining equipment

	Elec_Weight	NonEl_Weight		
			Share	
Function	Share	Fuel	Heat	Vehicle
Grinding	20%	Natural gas	80%	20%
Lighting	20%	Distillate	70%	30%
		Gasoline	0%	100%
Ventilation	60%	Coal	100%	0%
		Resid	100%	0%

Source: U.S. Energy Information Administration

Surface/Underground Mining Share

This component of the TPC reflects changes in the regional share of coal produced from underground mines. Surface and underground production is reported by the CMM and provided to the IDM for this calculation. Production is aggregated from the 14 coal regions to the 4 census regions, as follows:

$$CL\_Surface_{r,y} = \sum_{cr} PMTS_{r,y,cr}$$ (144)

$$CL\_Underground_{r,y} = \sum_{cr} PMTD_{r,y,cr}$$ (145)

where PMTS and PMTD represent the tons of coal produced on the surface and underground, respectively (from the Coal Market Module), and the 14 coal production regions are mapped to the 4 census regions as follows:

Table 16. Census region and coal region mapping

Census region	Coal regions
1	1
2	2 ,3, 6
3	4, 5, 7
4	8–14

Source: Commercial Demand Module

The fraction of annual production from underground mines is then given as follows:

$$Under\_Share_{r,y} = \frac{CL\_Underground_{r,y}}{\left(CL\_Underground_{r,y} + CL\_Surface_{r,y}\right)}$$ (146)

The marginal change in that share is given as follows:

$$Under\_Index_{r,y} = \frac{Under\_Share_{r,y}}{Under\_Share_{r,y-1}} - 1.0$$ (147)

Labor Productivity

Labor productivity is derived from one of the data input files, CLUSER.txt, employed by the CMM. Each of the production regions has forecasts of productivity by coal type; these are used to construct a production-weighted average productivity forecast, mapped to the census regions:

$$CL\_L\_Prod_{r,y,Surf} = \frac{\sum_{cr} B\_Prod_{r,Surf,cr} * L\_Prod_{r,Surf,cr,} * FR\_Prod_{r,y,Surf,cr}}{\sum_{cr} B\_Prod_{r,Surf,cr,} * L\_Prod_{r,Surf,cr}} \qquad (\,148\,)$$

where

$B\_Prod_{r,Surf,cr}$=Base year (2008) coal production by type and supply region;

$L\_Prod_{r,Surf,cr}$ =Base year labor productivity in tons/miner/hour by Tech and supply region;

$FR\_Prod_{r,y,Surf,cr}$ = Forecast year labor productivity by Tech Surf, supply region, and year y;

Cr = Census divisions summed to four census regions r; and

$Surf$= Mine type: 1 = Surface, 2 = Underground.

The productivity index is given as follows:

$$L\_Prod\_Index_{r,y,Surf} = 1.0 - \frac{CL\_L\_Prod_{r,y,Surf}}{CL\_L\_Prod_{r,y-1,Surf}} \qquad (\,149\,)$$

TPC calculation

The collective TPC by fuel type and region may now be explicitly calculated as follows:

$$\begin{aligned} TPC_{r,f,y} = \; & TPC\_Weight_{1,f} * Wt\_EQP\_Index_{f,y} \\ & + TPC\_Weight_{2,f} * Under\_Index_{r,y} \\ & + TPC\_Weight_{3,f} * Under\_Share_{r,y} * L\_Prod\_Index_{r,1,y} \\ + TPC\_Weight_{3,f} * \big(1.0 - Under\_Share_{r,y}\big) * L\_Prod\_Index_{r,2,y} \qquad (\,150\,) \end{aligned}$$

where the number index represents the weight associated with either the equipment (1), the underground coal production index (2), or the underground coal share (3).

The factor weights by region and fuel for mining equipment are as follows, based on analyst judgment:

Table 17. Technology possibility curve (TPC) equipment component weights by region

TPC_Weight $_{1,f}$	Electricity	Natural gas	Distillate	Gasoline	Coal	Residual
Region 1	70%	85%	90%	100%	70%	90%
Region 2	70%	85%	90%	100%	70%	90%
Region 3	70%	85%	90%	100%	70%	90%
Region 4	70%	85%	90%	100%	70%	90%

Source: U.S. Energy Information Administration

These may be changed if desired. The weights for the two remaining factors are then calculated as follows:

$$TPC\_Weight_{2,f} = \frac{\left(1.0 - TPC\_Weight_{1,f}\right)}{2} \quad\quad (\,151\,)$$

$$TPC\_Weight_{3,f} = 1.0 - \left(TPC\_Weight_{1,f} + TPC\_Weight_{2,f}\right) \quad\quad (\,152\,)$$

In other words, the difference between 1.0 and the equipment weighting factor is divided between the other two weights.

OIL AND GAS MINING

The OGSMTPC subroutine calculates the consumption of energy in the oil and natural gas extraction industry with the major exception of lease and plant fuel, which is natural gas fuel used for any purpose at the lease (extraction) site and fuel used in gas processing plants (lease and plant fuel is modeled in the Natural Gas Transmission and Distribution Model). All other fuels (residual fuel oil, distillate, motor gasoline, electricity, and NGL) are covered by OGSMTPC, as well as that natural gas that is not used in lease and plant fuel (that is, in natural gas liquid fractionators).

Energy consumption in this sector is largely driven by the number of wells drilled (related to oil and natural gas volumes) and their productivity.

The amount of fuel (f) demanded by the Oil and Gas Mining industry in year (y) is calculated as follows:

$$Q_{f,y} = OGMN_y * UEC_{f,y} \quad\quad (\,153\,)$$

where OGMN represents the value of domestic onshore oil and natural gas production, supplied by the MAM. The IDM calculates this quantity for each of the four census regions. The UEC (by fuel f) changes from year to year (year *y-1* to year *y*) according to the value of the TPC, as follows:

$$UEC_{f,y} = UEC_{f,y-1} * \left(1 + TPC_{f,y}\right) \qu\quad (\,154\,)$$

where the TPC indicates the marginal change in energy intensity from the previous year. The TPC is calculated as the weighted average of three indexes representing the marginal change in three factors: vehicle energy intensity, the regional productivity of oil and natural gas wells, and trends in the share of drilling that results in dry wells. Each of these components is described below.

Factor Indexes for Oil and Natural Gas Mining
Vehicle Energy Intensity

As noted in earlier sections, the freight truck model generates fuel economy estimates for three classes of truck. The contribution to the TPC is based on stock-weighted average fuel economy estimates of the truck population and the marginal change in vehicle energy intensity is defined and computed by fuel (f) and year(y) exactly as in *AGTPC* subroutine on page 83.

Productivity Factors

The Oil & Gas Supply Module (OGSM)[44] produces estimates of onshore oil and natural gas production for six production regions (PR), and seven product types (K) related to fuel types, as follows (the variable PROD_Wt is a measure of the relative difficulty of extraction, used in subsequent calculations):

Table 18. Relative difficulty of extraction of oil and natural gas

K	Product type	PROD_Wt
1	Conventional oil	1.0
2	Enhanced oil recovery	3.0
3	Conventional shallow gas	1.0
4	Conventional deep gas	1.0
5	Tight gas	3.0
6	Shale gas	2.0
7	Coal bed methane	3.0

Source: Oil & Gas Supply Module

Figure 11. *Annual Energy Outlook* oil and natural gas supply Regions
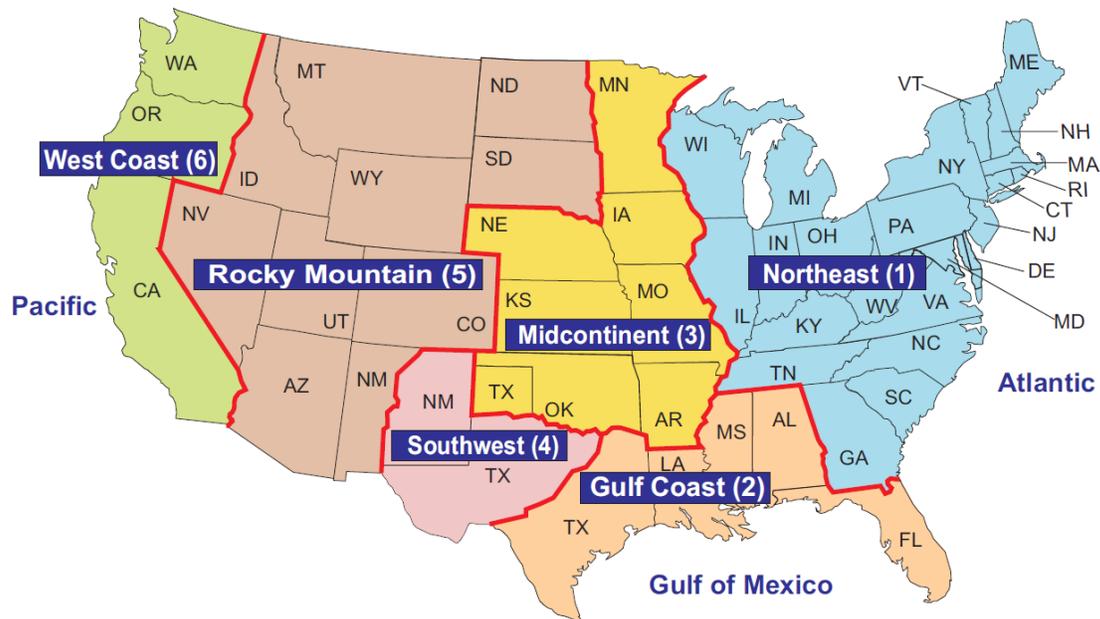
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2013*, p. 229.

The output from the production regions is first mapped to the corresponding census regions and converted from million barrels of oil and trillion cubic feet of natural gas) to trillion Btu, as follows:

$$OG\_Prod_{K,r,y} = \left[\sum_{PR=1}^{6} OGREGPRD_{PR,K,y} * OGSM\_Map_{PR,r} \right] * Convert_{Tech} \qquad (155)$$

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[44] https://www.eia.gov/outlooks/aeo/nems/documentation/ogsm/pdf/m063(2017).pdf

where

$OGREGPRD_{PR,K,y}$ = Regional production by production region PR, and fuel type K, from OGSM;

$OGSM\_Map_{PR,r}$ = Regional mapping factors, based on the geographic areas of states in each census region r, provided in the table below; and

$Convert_{Tech}$ = Conversion factor for oil (Tech=1) and natural gas (Tech=2).

Table 19. Oil & Gas Supply Module (OGSM) and census region mapping

OGSM_Map	OGSM production region					
	Northeast	**Gulf Coast**	**Midcontinent**	**Southwest**	**Rocky Mountains**	**West Coast**
Census region	**1**	**2**	**3**	**4**	**5**	**6**
1	22.9%	0.0%	0.0%	0.0%	0.0%	0.0%
2	38.0%	0.0%	71.3%	0.0%	15.5%	0.0%
3	39.1%	100.0%	28.7%	57.0%	0.0%	0.0%
4	0.0%	0.0%	0.0%	43.0%	84.5%	100.0%

Source: U.S. Energy Information Administration

The share of total production represented by oil is then calculated as follows:

$$Oil\_Share_{r,y} = \frac{\sum_{K=1}^{2} OG\_Prod_{K,r,y}}{\sum_{K=1}^{7} OG\_Prod_{K,r,y}} \qquad (156)$$

In addition, the oil and gas production factor, OG_ProdFac, representing the weighted average difficulty of extraction, is calculated as follows:

$$OG\_ProdFac_{r,y} = \frac{\sum_{K} OG\_Prod_{K,r,y} * PROD\_Wt_K}{\sum_{K} OG\_Prod_{K,r,y}} \qquad (157)$$

where

f = 1,2 for Oil (1 = conventional oil, 2 = enhanced oil recovery);

= 3-7 for Natural Gas (Tech = 2), (3 = conventional shallow gas, 4 = conventional deep gas, 5 = tight gas, 6 = shale gas, 7 = coalbed methane).

The Productivity Index is then calculated as follows:

$$Prod\_Index_{r,y} = Oil\_Share_{r,y} * \left[\frac{OG\_ProdFac_{Tech=1,r,y}}{OG\_ProdFac_{Tech=1,r,y-1}} - 1.0 \right]$$
$$+ \left(1.0 - Oil\_Share_{r,y}\right) * \left[\frac{OG\_ProdFac_{K=2,r,y}}{OG\_ProdFac_{K=2,r,y-1}} - 1.0 \right] \quad (158)$$

Dry Well Index

Another factor affecting the TPC is the share of drilling that produces dry wells. Growth in this factor is assumed to correlate with increased energy required for overall extraction. The data for successful and dry wells are obtained from the OGSM and are mapped from the six production regions (PR) to the four census regions (r), as follows:

$$Success\_Well_{K,r,y} = \sum_{PR=1}^{6} ogsrl48_{PR,K,y} * ogwellsl48_{PR,K,y} * OGSM\_Map_{PR,r} \qquad (159)$$

$$Dry\_Well_{K,r,y} = \sum_{PR=1}^{6} (1.0 - ogsrl48_{PR,K,y}) * ogwellsl48_{PR,K,y} * OGSM\_Map_{PR,r} \qquad (160)$$

$$Total\_Well_{K,r,y} = Success\_Well_{K,r,y} + Dry\_Well_{K,r,y} \qquad (161)$$

where

$ogsrl48_{PR,K,y}$ = Share of successful wells by production region PR product type K, and year y;

$ogwellsl48_{PR,K,y}$ = Total wells drilled, by region and type; and

$OGSM\_Map_{PR,r}$ = Regional mapping factors, based on the geographic areas of states in each region, described above.

The production-weighted average dry well percentage by census region is then calculated as follows:

$$Wtd\_OG\_WellFac_{r,y} = \frac{\frac{\sum_K Dry\_Well_{K,r,y}}{\sum_K Total\_Well_{K,r,y}} * OG\_Prod_{K,r,y}}{\sum_K OG\_Prod_{K,r,y}} \qquad (162)$$

The Well Index is expressed as the change in this factor from the previous year:

$$Well\_Index_{r,y} = Wtd\_OG\_WellFac_{r,y} - Wtd\_OG\_WellFac_{r,y-1} \qquad (163)$$

TPC calculation

The collective TPC by fuel type and region may now be explicitly calculated as follows:

$$TPC_{f,r,y}$$
$$= TPC\_Fac\_Wt_{f,1} * VEH\_Index_{f,y}$$
$$+ TPC\_Fac\_Wt_{f,2} * Prod\_Index_{r,y} + TPC\_Fac\_Wt_{f,3} * Well\_Index_{r,y} \qquad (164)$$

where TPC_Fac_Wt represents ad hoc weighting factors within each fuel type indicating the influence of each of the index factors described above. These assumed factors are provided in the following table.

Table 20. Technology possibility curve (TPC) factor weights by fuel *(TPC_Fac_Wt)*

Fuel	Vehicle index	Productivity index	Dry well index
Electricity	0.00	0.80	0.20
Natural gas	0.50	0.40	0.10
Distillate	0.50	0.40	0.10
Gasoline	0.50	0.40	0.10
Renewables	0.00	0.80	0.20
Residential	0.00	0.80	0.20

Sources: Oil and Gas Supply Module and Transportation Demand Module

OTHER MINING

The OTH_MINTPC subroutine calculates the consumption of energy for mining metals and minerals, which constitute all other mining sub-sectors. As in the COALTPC subroutine, energy usage for grinding equipment used in this sector is evolved parallel to grinding equipment in the cement industry. In addition, like the COALTPC subroutine, the distinction between surface and sub-surface mining is made, which governs a large portion of energy consumption patterns in this industry.

The amount of fuel (f) demanded by the Other Mining (Metals & Minerals) industry in year (y) is calculated as follows:

$$Q_{f,y} = OTHMN_y * UEC_{f,y}$$ (165)

where OTHMN represents the value of metals and non-metals mining production, supplied by the Macroeconomic Activity Module(MAM). The IDM calculates this quantity for each of the four census regions. The UEC changes from year to year according to the value of the TPC, as follows:

$$UEC_{f,y} = UEC_{f,y-1} * (1 + TPC_{f,y})$$] (166)

where the TPC indicates the marginal change in energy intensity in year *y* from the previous year *y-1*. The TPC is calculated as the weighted average of three indexes representing the marginal change in two factors: equipment efficiency, and the labor productivity of surface mining, obtained from the coal model. The TPC is further subdivided between Metal Mining and Non-Metal Mining, in recognition of their different characteristics. These indexes are described in detail below.

Other Mining Macroeconomic split
Total Mining shipments are reported at the regional level by the MAM, but the metals/non-metals components are available only at the national level within the Global Insight Macroeconomic Model (GI Model). Accordingly, it is necessary to infer what share of regional mining output consists of metals. At present, the national metals share is included as a data statement, but it is possible to extract it from the GI (Global Insights) model as follows:

$$MetlShr_y = \frac{R2122R\_1_y}{R2122R\_1_y + R2123R\_1_y}$$ (167)

where

$R2122R\_1_y$ =Annual value of Metals production from the GI Model, by year y; and

$R2123R\_1_y$ =Annual value of Non-Metals production from the GI Model, by year y.

This share is regionalized by reference to the 2006 Census of Employment and Wages (CEW), which provides estimates of employment in the mining industries, by state. The following data is used to determine what fraction of each region's mining output may be attributed to metals. The matrix **Reg_MetlShr** is contained in an input file shown in Table 21 and is held static.

Table 21. Metal and nonmetal shares by census region

Census region	Number of employees (thousands)			Normalized share
	Metal	Non-metal	Metal share	Reg_MetlShr
1	-	1,807	0.00%	0.0%
2	3,490	19,382	15.26%	21.0%
3	413	27,859	1.46%	2.0%
4	22,491	17,742	55.90%	77.0%

Source: U.S. Census Bureau

Note: These factors are used in the final calculation of the technology possibility curve, below.

Factor Indexes for Other Mining
Labor Productivity

Labor productivity is defined and calculated on page 93.

Equipment

The weighted equipment index is defined and calculated on page 89.

Grinding Equipment

From the results of the cement submodule on page 102, the average efficiency of raw grinding equipment per year, or $Raw\_Grind\_Eff_y$, is extracted to use as a proxy for changes in the energy intensity of mining equipment.

Vehicle Energy Intensity

The freight truck model generates fuel economy estimates for three classes of truck. The contribution to the TPC is based on stock-weighted average fuel economy estimates of the truck population, and the marginal change in vehicle energy intensity is defined and computed by fuel (f) and year(y) exactly as in *AGTPC* subroutine on page 83.

The weighted equipment index is then calculated for Metals and Non-Metals separately.

For Electricity (Metals Mining), the calculation is as follows:

$$Wt\_Met\_EQP\_Index_{f,r,y} = \left[\frac{Raw\_Grind\_Eff_y}{Raw\_Grind\_Eff_{y-1}} - 1.0\right] * Elec\_Met\_Weight_{Grind}$$

$$+ \left[\frac{WHSE\_LightIndex_{r,y}}{WHSE\_LightIndex_{r,y-1}} - 1.0\right] * Elec\_Met\_Weight_{Light}$$

$$+ \left[\frac{WHSE\_VentIndex_{r,y}}{WHSE\_VentIndex_{r,y-1}} - 1.0\right] * Elec\_Met\_Weight_{Vent} \qquad (168)$$

where the difference in the calculation is in the relative weights ascribed to Grinding, Lighting, and Pumping (through its proxy, ventilation). The calculation for nonmetals is similar, using weights for nonmetallic mining. These factors are as follows:

Table 22. Electric equipment weights

	Variable	Grinding	Lighting	Pumping
Metals	Elec_Met_Wt	0.20	0.20	0.60
Non-metals	Elec_NM_Wt	0.60	0.20	0.20

Sources: Commercial Demand Module (for lighting and pumping), Industrial Demand Module Cement submodule (for grinding)

For Other Fuels (Metals), the calculations are as follows:

$$Wt\_Met\_EQP\_Index_{f,y} = \left[\frac{WHSE\_HeatIndex_{f,r,y}}{WHSE\_HeatIndex_{f,r,y-1}} - 1.0\right] * Elec\_Met\_Weight_{Heat,f}$$

$$+ VEH\_Index_{f,y} * NonEl\_Met\_Weight_{Vehicle,f} \qquad (169)$$

where the current weighting factors for Metals and Non-Metals are identical. The calculation for non-metals is similar, using weights for nonmetal mining. The model assigns the same weights to the two variables to make subsequent, user-specified changes easier to implement.

Table 23. Non-electric equipment weights (metals and non-metals)

TPC_Met_Wt $_{r,1,f}$ and TPC_NM_Wt $_{r,1,f}$					
	Natural gas	Distillate	Gasoline	Coal	Residual
Heating	80%	70%	0%	100%	100%
Vehicles	20%	30%	100%	0%	0%

Source: Commercial Demand Module and Transportation Demand Module

TPC calculation

The collective TPC by fuel type f and region r may now be explicitly calculated as follows:

$$TPC_{r,f,y} = \left[\begin{array}{l} TPC\_Met\_Wt_{r,1,f} * Wt\_Met\_EQP\_Index_{r,y} \\ + TPC\_Met\_Wt_{r,2,f} * L\_Prod\_Index_{r,y} \end{array}\right] * MetlShr_y * Reg\_MetlShr_r$$

$$+ \begin{bmatrix} TPC\_NM\_Wt_{r,1,f} \ * \ Wt\_NM\_EQP\_Index_{r,y} \\ + \ TPC\_NM\_Wt_{r,2,f} \ * \ L\_Prod\_Index_{r,y} \end{bmatrix} * \left(1.0 - MetlShr_y * Reg\_MetlShr_r \right) \quad (\ 170\ )$$

where the TPC Equipment Index weights for both Metals and Non-Metals are provided in the following table, based on analyst judgment:

Table 24. Technology possibility curve (TPC) equipment component weights by region

	TPC_Met_Wt r,1,f	and TPC_NM_Wt r,1,f				
Metal and non-metal	**Electricity**	**Natural gas**	**Distillate**	**Gasoline**	**Coal**	**Residual**
Region 1	70	85%	90%	100%	90%	90%
Region 2	70	85%	90%	100%	90%	90%
Region 3	70	85%	90%	100%	90%	90%
Region 4	70	85%	90%	100%	90%	90%

Source: U.S. Energy Information Administration

The non-equipment (that is, labor productivity) index weights are then calculated as follows:

$$TPC\_Met\_Wt_{r,1,f} = \ 1.0 - TPC\_Met\_Wt_{r,1,f} \qquad\qquad (\ 171\ )$$

As with the non-electric equipment weights, above, the factors are identical across regions and for Metals and Non-Metals mining. This explicit separation of the two mine types in the code provides an easily adaptable structure for testing and scenario development.

Specialized submodules for process flow industries

Common technical choice subroutines for the process flow industries

For the iron-and-steel and paper industries, common subroutines are used where possible when calculating energy use, needed capacity, and technology choice wherever possible. Because industries differ in process steps and products, common subroutines are not always possible.

- o Tech_Step: the main process flow subroutine that reports energy consumption by fuel for each technology, needed productive capacity, and technology chosen for that capacity. Tech_Step calls these subroutines. Tech_Step is also used in cement, lime, glass, and aluminum.

- o Step_Capacity: computes needed capacity for each process step based on product demand and retirement rates.

- o Logit_Calc: determines which technologies are chosen for each process step.

Subroutine Step_Capacity

For each process step, there is a demand for production defined by the sum of regional PRODCUR elements. After establishing the output of a given step, it is necessary to determine whether additional

processing capacity will be needed. The maximum process output between 2006 and 2014 is assumed to represent existing baseline capacity, which is then held constant through 2011. In each year following the base year, incremental additions to capacity are based on the following assumptions:

- Baseline capacity is retired at a linear rate over a fixed time frame (initially set to 20 years).

- Production demand in excess of surviving baseline capacity will be met with replacement equipment.

- Equipment acquired after 2014 will retire according to a logistic decay function.

Calculating surviving and needed capacity are the first two steps.

$$Surviving\_Cap_{j,y} = BaseCap_{j,y} + Surv\_Incr\_Adds_{j,y} \qquad (172)$$

$$Needed\_Cap_{j,y} = \text{MAX} \left(SumProdCur_{j,y} - Surviving\_Cap_{j,y}, 0 \right) \qquad (173)$$

where, for the current year y and step j,

$BaseCap_{j,y}$ =	=	Surviving baseline production capacity;
$Surv\_Incr\_Adds_{j,y}$	=	Surviving incremental capacity added before the current year y;
$Needed\_Cap_{j,y}$	=	Incremental production capacity required;
$SumProdCur_{j,y}$	=	Total production capacity required to meet demand. Calculation details are on page 135;
$Needed\_Cap_{j,y}$	=	Incremental production capacity required;
$BaseCap_{j,y}$	=	Surviving baseline production capacity.

There are two components of surviving capacity: base capacity and previously added capacity. Surviving baseline capacity is calculated as follows:

$$BaseCap_{j,y} = BaseCap_{j,y-1} - \left[\frac{BaseCap_{j,BaseYr}}{BaseCap\_Life} \right] \qquad (174)$$

where

$BaseCap_{\ BaseYr}$	=	Initial value of baseline production capacity for base year $BaseYr$; and
$BaseCap\_Life$	=	Assumed lifetime of baseline capacity, provisionally set to 20 years.

For equipment added to meet incremental demand in previous years, the calculation is as follows:

$$Surv\_Incr\_Adds_{j,y}$$
$$= \sum_{ii=BaseYr}^{y-1} Surviving_{ii,y} * \left[\sum_{Tech=1}^{MaxTech} Added\_Cap_{j,Tech,i} \right] \qquad (175)$$

$$Surviving_{ii+1,y} = \frac{1}{1 + \exp\left[-Calib * \left(1.0 - \left[\frac{2.0 * (y - ii)}{Lifetime}\right]\right)\right]}$$ (176)

where

$Added\_Cap_{j,Tech,i}$	=	Capacity added for step j, technology $Tech$, in year i.
$Lifetime$	=	Assumed lifetime of added capacity;
$Calib$	=	Calibration constant for the survival curve; and
i	=	Year capacity was added

The survival function determines the share of capacity added in a given year that survives to the current year, as shown in Figure 12.

Figure 12. Example of new capacity survival function

percent of new capacity in service

age of new capacity (0=year added)
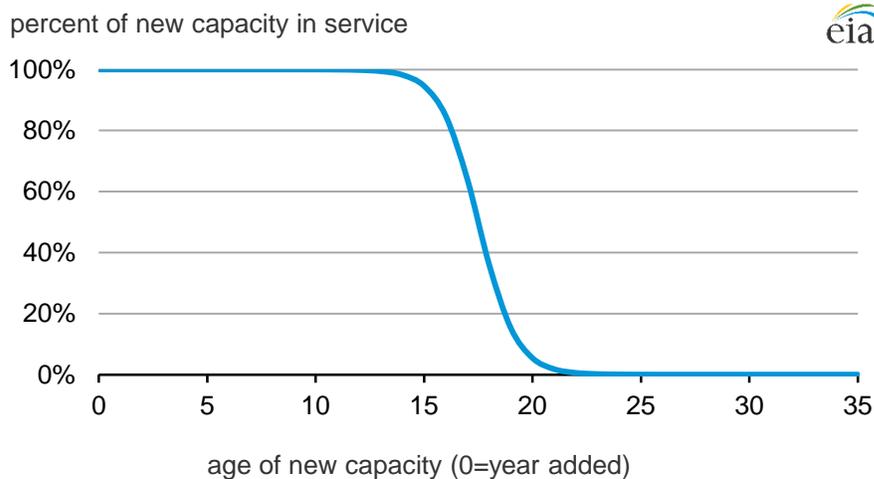
Source: calculation based on input file ironstlx.xlsx

After establishing the required additions to production capacity, $Needed\_Cap_i$ must be allocated amongst competing technologies.

Subroutine Logit_Calc

New capacity is allocated using a multinomial logit model, in which the characteristics of competing alternatives are assessed. Each alternative technology has identifying characteristics, in this case, the capital cost, O&M cost, fuel use, steam demand, and CO_2 emissions associated with the production of a kilotonne of output. These characteristics are extracted from the CIMS database, which contains detailed data for each component in the steel manufacturing process. These characteristics are summarized in the appropriate sections, below:

$$U_{j,Tech,y} = Alpha_{j,Tech} * Decay\_Fctr_{j,y} + (\beta_1 * Tot\_Cost_{Tech})$$

$$+ \beta_2 * \left(\sum_f Fuel\_Use_{j,Tech,f,y} * Fuel\_Cost_{f,y} + Steam\_Use_{j,Tech} \right)$$

$$+ \left(\beta_3 * CO2Emiss_{j,Tech} * CO2\_Cost_y \right) + Scale\_Factr \qquad (\,177\,)$$

where

$U_{j,Tech,y}$	=	Equipment utility, referred to in the code as *logit_comp* for step j, technology $Tech$, and year y;
β_i	=	Scaling coefficient for each technology attribute, i, identified in the code as "*calibrationc*";
$Alpha_{j,Tech}$	=	Alternative-specific constant (ASC) for step j and technology $Tech$, that ensures initial shares comport with historical values, described further below;
$Decay\_Fctr_{j,y}$	=	Alpha-decay factor for step j and year y, that reduces the ASC to zero over time, described below;
$Scale\_Fctr$	=	Dynamically-calculated scaling factor that ensures that the Fortran calculations will not go out of bounds & crash the program;
$Tot\_Cost_{j,Tech}$	=	Equipment fixed costs per kilotonne of output for step j and year y;
$Fuel\_Use_{j,Tech}$	=	Energy intensity of each fuel used by technology $Tech$ in step j, in MMBtu/kilotonne;
$Fuel\_Cost_{f,y}$	=	Price of energy, in \$/MMBtu; for the associated fuel f in year y;
$Steam\_Use_{j,Tech}$	=	Steam service demand for technology $Tech$ in year y, in GJ/kilotonne of output;
$CO2Emiss_{j,Tech}$	=	CO2 emissions for technology $Tech$ in step j, in kilotonnes/kilotonne of output; and
$CO2\_Cost_y$	=	CO2 emissions cost in year y, in \$/kilotonne, exogenously specified.

The market shares of the competing production technologies are then calculated as follows:

$$Tech\_Shares_{j,Tech,y} = \frac{\exp(U_{j,Tech,y})}{\sum_{Tech} \exp(U_{j,Tech,y})} \qquad (\,178\,)$$

Alpha, the alternative-specific constant, is a scaling factor that ensures that initial shares of technology match the exogenously specified baseline shares. This scaling is done through a recursive process in the model's base year, in which all alphas are iteratively replaced as follows:

$$Alpha_{j,Tech,z} = Alpha_{j,Tech,z-1} + \ln\left(\frac{ExogShare_{j,Tech}}{Tech\_Shares_{j,Tech,BaseYr}}\right) \tag{179}$$

where

$Alpha_{j,Tech,z}$ = Alternative specific constant for step j, technology $Tech$, and iteration z;

$ExogShare_{\ Tech}$ = Exogenously-specified baseline share for the technology Tech; and

$Tech\_Shares_{j,Tech,BaseYr}$ = Calculated baseline share for step j, technology $Tech$, at base year $BaseYr$, using specified coefficients.

This process continues until all alphas converge to within a specified tolerance; specifically, when the magnitude of change between iterations falls below 0.001, or $(Alpha_{j,Tech,z} - Alpha_{j,Tech,z-1}). < 0.001$. The alphas are subsequently held constant.

The decay factor reduces the effect of this constant over time so that the incremental additions of technology are increasingly determined by their attributes. The decay function is expressed as follows:

$$Decay\_Fctr_y = exp\left(\frac{-alpha\_decay_1 * (y - 2011) * ln(2)}{alpha\_decay_2}\right) \tag{180}$$

Where *alpha_decay₁* and *alpha_decay₂* are user-specified parameters that determine the rate of decay.

The total production, by technology, is given by the following:

$$Tot\_Prod\_Tech_{j,Tech,y} = BaseCap_j * Base\_Tech\_Share_{j,Tech}$$

$$+Surv\_Added\_Cap_{j,Tech,y} + Tech\_Shares_{j,Tech,y} * Add\_Cap_{j,y} \tag{181}$$

where

$BaseCap_j$ = Capacity for step j in the base year

$Base\_Tech\_Share_{Tech}$ = Base year shares of production technology $Tech$.

$Surv\_Added\_Cap_{j,Tech,y}$ = $\sum_{ii=BaseYr}^{y-1} Surviving_{ii,y} * Added\_Cap_{j,Tech,ii}$ is surviving added capacity for step j, technology $Tech$, and year y. The variables $Surviving_{ii,y}$ and $Added\_Cap_{j,Tech,i}$ are defined on page 103

CEMENT INDUSTRY

Figure 13 shows a detailed process flow diagram (PFD) for cement manufacturing. Raw materials containing calcium, silicon, aluminum, iron, gypsum, and small amounts of other ingredients are crushed and ground in ball mills, roller mills, or both. The mining and transport of raw materials to the plant site are excluded in the cement model as these operations are modeled in a separate module of NEMS. Internal submodule calculations are in metric units, which are converted to English units for calculations external to this submodule.

Figure 13. Cement industry detailed process flow
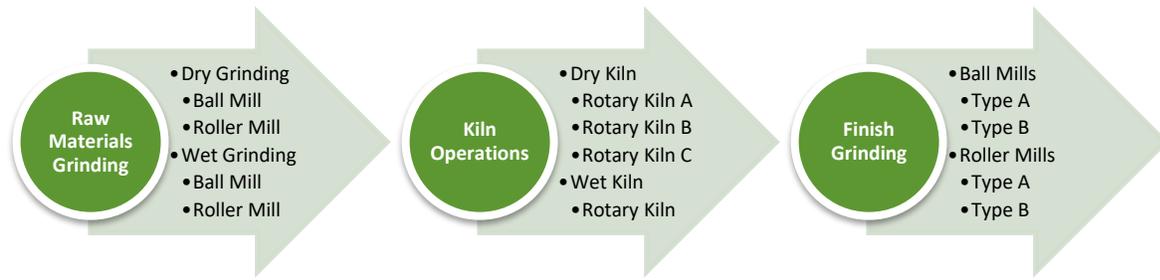
Source: U.S. Energy Information Administration

The raw materials are ground dry or combined with water to form slurry (categorized as dry processing or wet processing). Wet grinding reduces grinding energy consumption, but increases the energy consumption for evaporating the added water. The crushed raw materials enter a kiln (often preceded by a pre-heater system) and are exposed to high temperatures (~2,700°F/1500°C). U.S. kilns are commonly fired by coal, with natural gas and oil as a starter or backup fuel. Recently, alternative fuels such as tires and industrial waste have been used as supplementary fuels. The kiln converts the raw materials mixture into clinker, which is then cooled rapidly to prevent further chemical changes. The cooled clinker is blended with additives and ground into a fine powder that is cement. The cement may be bagged or transported in bulk to retail stores and commercial users.

Because of the chemistry of cement production, mass flows through each major unit operation will not be the same. For this reason, the calculation of mass flows through each unit operation will begin at the end of the PFD—that is, the annual production of cement in the finish grinding operation.

Figure 14. Cement submodule process steps
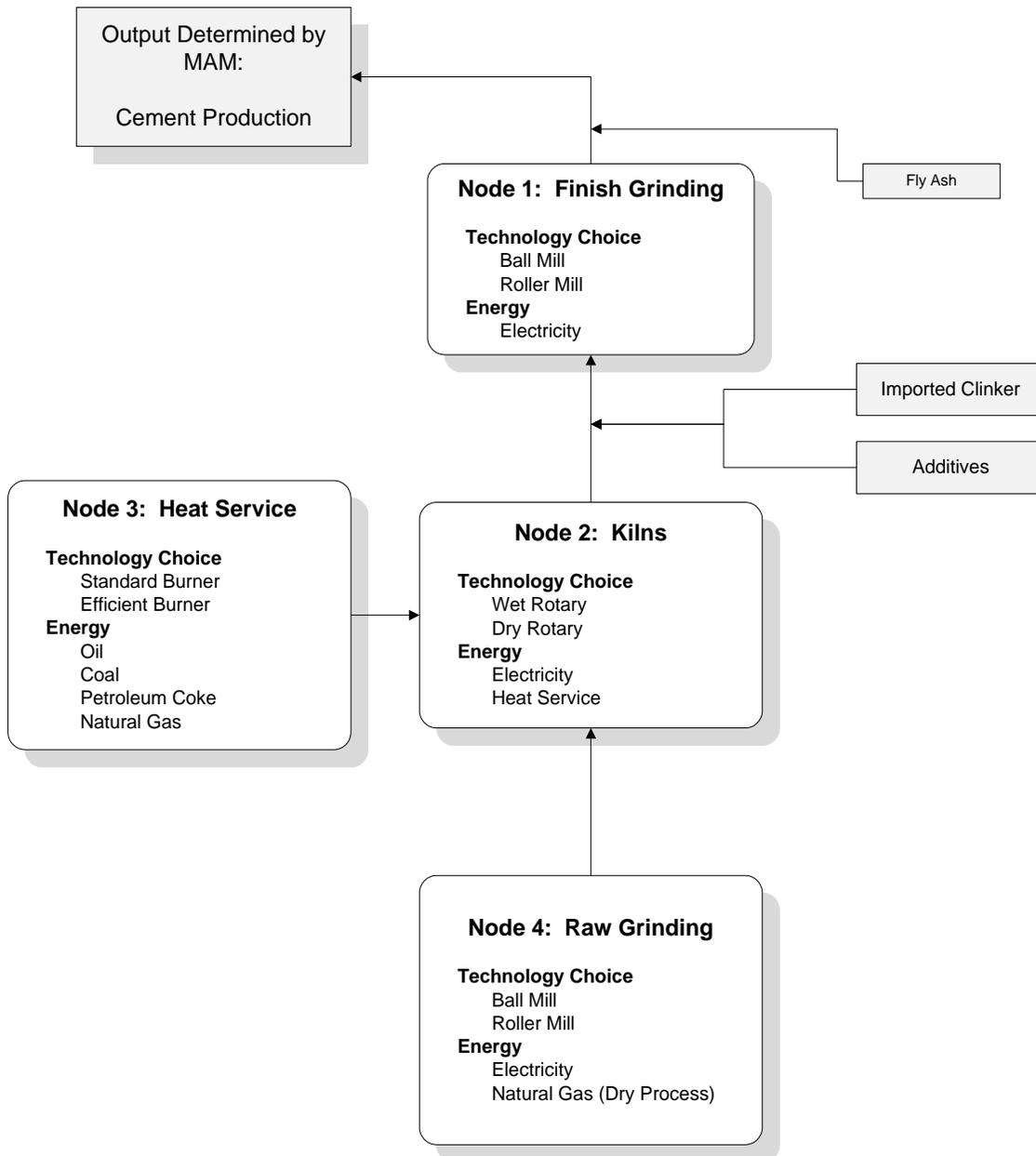
Source: U.S. Energy Information Administration

FINISH_GRIND_CAP (Node 1)

The FINISH_GRIND_CAP subroutine represents cement production capacity requirements for the IDM.

The output of the Finish Grinding node is the total quantity of cement shipments (in thousand metric tons) in a given year, as follows:

$$Output_y = \text{Output\_IBYR2} * \left[\frac{OUTIND_{11,y}}{CEMENTIBYR} \right] \qquad (182)$$

where

$Output_y$	=	Physical quantity of cement shipments, in thousands of metric tons, projected for the cement industry;
$Output\_IBYR2$	=	Physical quantity of cement shipments, in thousands of metric tons in 2014, as reported by the U.S. Geological Survey as more representative than the 2014 post-recession values in terms of projections;
$OUTIND_{11,y}$	=	Gross value of shipments for the cement industry (IDM industry code of 11) for the nation in the year current projection year, as determined by NEMS MAM; and
$CEMENTIBYR$	=	Gross value of shipments for the cement industry for the nation in year 2014, as determined by MAM.

The output requirements of the finish grinders are reduced by the inclusion of certain additives, such as fly-ash, following the grinding step:

$$Grinding\_Tonnes_y = Output_y \quad * (1.0 - FlyAsh) \tag{183}$$

where

$Grinding\_Tonnes_y$	=	Quantity of output from the finish grinding step in year y, in thousands of metric tons; and
$FlyAsh$	=	Percentage of additives, which is currently held constant at 5.0%.

Cement production in 2014 represents existing baseline capacity, which is allocated among the four competing types of finish grinders as follows:

$$BaseCapF_{Tech} = Grinding\_Tonnes * Tech\_Share_{Tech} \tag{184}$$

where

$BaseCapF_{Tech}$ =		Initial baseline capacity, by equipment Tech;
$Grinding\_Tonnes_y$	=	Quantity of output from the finish grinding step, in thousands of metric tons; and
$Tech\_Share_{Tech}$	=	Initial allocation of finish grinding capacity, based on CIMS data, for 2008.

For each year following the base year (that is, 2014), incremental additions to Finish Grinding capacity are based on the following assumptions:

- o Baseline capacity is retired at a linear rate over a fixed time frame (initially set to 20 years).

    o   Production demand in excess of surviving baseline capacity will be met with replacement equipment.

    o   Equipment acquired after 2014 will retire according to a logistic function.

Baseline capacity that survives, the survival of any added incremental capacity, and needed capacity are calculated in subroutine Step Capacity, which is described starting on page 102. The survival function determines the share of needed capacity added in a given year that survives to the current model year, as shown in Figure 12 on page 104.

After establishing the required additions to finish grinding capacity, the CEMENT_INDUSTRY submodule allocates the current model year's added capacity among competing technologies in subroutine Logit_Calc, which is described beginning on 104.

KILN_CAPACITY *(Node 2)*

Process heat service required by the kilns is addressed in this node. Wet process and dry process capacity are treated differently, due to the obsolescence of the wet process and the decision not to replace retiring wet capacity. Accordingly, the heating systems associated with the wet process are assumed to be retired at the same rate as the kilns they service.

Kilns provide the clinker for the finish grinding step, so total kiln output/capacity is linked to the previous node. Historically, a certain fraction of the material proceeding to the finish grinding step consists of imported clinker and other additives. This process reduces the needed capacity of kilns, as follows:

Baseline kiln capacity (that is, output in 2014 and earlier years) is distributed between wet and dry processes, and it is further allocated among different kiln technologies according to historical production shares, from Consolidated Impacts Modeling System (CIMS), as follows:

$$Wet\_Process_{Baseyear} = Process\_OutputK_{Baseyear} * pWet \qquad (\,185\,)$$

$$Dry\_Process_{Baseyear} = Process\_OutputK_{Baseyear} * (1 - pWet) \qquad (\,186\,)$$

where

$Wet\_Process_{Baseyear}$ =Wet process capacity in base year;

$pWet$ =Historical share of wet process output, 13.8%, in 2014;

$Dry\_Process$ = Dry process capacity in base year; and

$Process\_OutputK$ = Total output from cement kilns, in thousands of metric tons.

For the 2014 year, storing of values for subsequent computations occurs as follows:

$$Wet\_RotaryIBYR_{Baseyear} = Wet\_Rotary_{Baseyear} \qquad (\,187)$$

$$Dry\_Rotary_{Tech,Baseyear} = Dry\_Process_{Tech,Baseyer} * Tech\_Share_{Tech,Baseyear} \qquad (188\,)$$

$$Dry\_RotaryIBYR_{Tech,Baseyear} = Dry\_Rotary_{Tech,Baseyear} \qquad (189)$$

where

$Tech\_Share_{Tech,Baseyar}$ =   Allocation shares of dry rotary kilns, CIMS data;

$Wet\_RotaryIBYR_{Baseyear}$ =   Wet process capacity in 2014 base year; and

$Dry\_RotaryIBYR_{Tech}$ =   Dry process capacity, by equipment Tech in 2014 base year.

Baseline capacities in subsequent years are calculated using the formula on page 103.

The survival of any added incremental capacity is based on a logistic function, $New\_Cap\_ServK_i$, which is similar to $Surv\_Incr\_Adds_{j,y}$, described on page 103. The survival function determines the share of needed capacity added in a given year that survives to the current model year, as shown in in Figure 12 on page 104.

Then any needed added incremental capacity, stored and retained by model year, for the current model year is determined by both surviving baseline and surviving incrementally added capacity as follows:

$$Needed\_Capacity_y = Process\_OutputK_y - Surviving\_Capacity_y \qquad (190)$$

Calculation details for $Needed\_Capacity_y$ and $Surviving\_Capacity_y$ are described in subroutine Step Capacity, which is described starting on page 102.

The use of the wet process is considered to be declining and is consequently not subject to replacement by new, similar technologies. Because of different input process (for example, raw grinding) requirements associated with the wet process, it needs to be tracked separately, and retirements are accommodated by additions to dry process technology. Any added incremental capacities for dry rotary kilns are subsequently allocated to kiln Type in the KILN_ALLOCATION subroutine.

FINISH_GRIND_ALLOC New capacity is allocated in the FINISH_GRIND_ALLOC subroutine using a multinomial logit model, in which the characteristics of competing alternatives are assessed. Each alternative technology has identifying characteristics, in this case, the capital cost, operations and management (O&M) cost, fuel use, and particulate emissions associated with the production of a thousand metric tons of cement. These characteristics are extracted from the CIMS database, which contains detailed data for each component in the cement manufacturing process. Each multinomial logit model used in allocating equipment types is initially calibrated to provide the baseline shares of equipment. The annual market share for each new technology is calculated in subroutine Logit_Calc, which is described starting on page 104.

KILN_ALLOCATION
As noted above, all additional kiln capacity is expected to be provided by dry process kilns, and the allocation of incremental demand is governed by the characteristics of the competing dry-process technologies, based on a multinomial logit model. Each multinomial logit model used in allocating equipment types is initially calibrated to provide the baseline shares of equipment, as shown above.

After these market shares are applied to the incrementally added production capacity, coupled with the surviving production capacity from both the wet and dry process kilns, the heat demand in total cement kilns is determined as follows:

$$Heat\_Demand_y = \sum\nolimits_{Tech} Heat\_Req_{Tech,y} \qquad (191)$$

where

$Heat\_Demand_y$ =   Total amount of heat demand, as expressed in gigajoules (GJ), to produce $Process\_OutputK$, as expressed in thousands of metric tons of clinker; and

$Heat\_Req_{Tech,y}$ =   Heating requirements, by kiln process $Tech$, based on clinker production and reported CIMS energy requirements.

The heat (that is, $Heat\_Req_{Tech,y}$) required to produce this output (expressed in GJ) is calculated separately for each process and subsequently totaled and passed to the CEMENT_INDUSTRY's subroutine BURNER_CAP, as the variable $Heat\_Demand$ and $Heat\_Req_{1,y}$ (that is, 1 index denotes heating requirement for wet process kilns).

According to CIMS data, the electricity used in wet process kilns is produced in a CHP system that also provides the required process heat service. Accordingly, these kilns are net producers of electricity, and this component of the electric energy requirement is expressed as a negative in the CEMENT_INDUSTRY submodule's output.

In the base year, 2014, total process heat requirement, calculated in subroutine KILN_ALLOCATION, is allocated among the available burner types, determined as follows:

$$Heat\_Demand_y = \sum_{Tech} Heat\_Req_{Tech,y} \qquad (192)$$

$$Wet\_Heat_y = Heat\_Req_{1,y} \qquad (193)$$

$$Dry\_Heat\_Req_y = \sum_{Tech=2}^{numtech} Heat\_Req_{Tech,y} \qquad (194)$$

where

$Heat\_Demand_y$ =   Total amount of heat demand, as expressed in gigajoules (GJ) of burner output, to produce $Process\_OutputK$, as expressed in thousands of metric tons of clinker;

$Heat\_Req_{Tech,y}$ =   Heating requirements, by kiln process $Tech$, based on clinker production and reported CIMS energy requirements—in other words, wet process is denoted as type 1;

Wet_Heat_y = Heat demand for wet process kilns; and

$Dry\_Heat\_Req_y$ = Total heat demand for dry process kilns.

For years after the base year, heat requirements for each technology are calculated similar to the function $Tot\_Prod\_Tech_{j,Tech,y}$, shown on page 106.

Wet process heating systems are treated differently, in that the allocation of boiler types remains static at 2014 shares because wet process kilns is considered as declining linearly in IDM model projections.

The survival function determines the share of needed capacity added in a given year that survives to the current model year, as shown in in Figure 12 on page 104. Then any needed added incremental dry heating capacity, stored and retained by model year, for the current model year is determined by both surviving baseline and surviving incrementally added heating capacity as follows:

$$Needed\_Capacity_y = Dry\_Heat\_Req_y - Surviving\_Capacity_y \qquad (195)$$

$Needed\_Capacity_y$ and $Surviving\_Capacity_y$ are calculated in subroutine Step Capacity, which is described starting on page 102.

The initial allocation of burners is defined below:

Table 25. Initial allocation of cement kiln burners

Type	Description	Initial share shares $_{Type, 2014}$
Natural gas 1	Standard natural gas-fired burner	0.6%
Natural gas 2	Efficient natural gas-fired burner	2.1%
Oil 1	Standard oil burner	0.5%
Oil 2	Efficient oil burner	1.7%
Coal	Standard coal burner	73.1%
Petroleum coke	Standard petroleum coke burner	22.0%

Source: SAIC, *Model Documentation Report: The U.S. Cement Industry*, unpublished data report prepared for the Office of Energy Analysis, U.S. Energy Information Administration, Washington, DC, August 2012.

BURNER_ALLOCATION

As with the other nodes, needed capacity additions, yielding $Needed\_Capacity_y$ and $Surviving\_Capacity_y$ are calculated in subroutine Step Capacity, which is described starting on page 102. The annual market share for each new technology is calculated in subroutine Logit_Calc, which is described starting on page 104.

RAW_GRIND_CAP (Node 4)

The clinker output from the kilns in Node 2 governs the required demand in the Raw Grinding step of the CEMENT_INDUSTRY submodule. The model treats the dry and wet processes separately. The quantity of material passing through the raw grinding step is calculated as follows:

$$Dry\_Process\_Out_y \ = \ Process\_OutputK_y \ - \ Wet\_Process_y \qquad (\ 196 \ )$$

$$Raw\_Material_y = \ Dry\_Process\_Out_y \ast MassLoss \qquad (\ 197 \ )$$

where

$Dry\_Process\_Out$	=	Quantity of clinker, in thousand metric tons, produced using dry process, as determined from Node 2;
$Process\_OutputK$	=	Total quantity of clinker, in thousand metric tons, produced as determined from Node 2;
$Wet\_Process_y$	=	Quantity of clinker, in thousand metric tons, produced using wet process, as determined from Node 2 by year y;
$Raw\_Material$	=	Raw material throughput for dry process, in thousands of metric tons; and
$MassLoss$	=	Mass Loss Ratio, set to 1.60.

Wet and dry process grinders have different characteristics and initial allocations, as shown in Table 26:

Table 26. Initial allocations of process grinders

Type	Description	Initial share
Dry process grinders		$Shares_{Type,2014}$
Ball mill	Dry raw grinding ball mill	43%
Roller mill	Dry raw grinding roller mill	57%
Wet process grinders		$Tech\_Split_{Type}$
Ball mill	Wet raw grinding ball mill	49%
Autogenous mill	Wet raw grinding autogenous mill	51%

Source: SAIC, *Model Documentation Report: The U.S. Cement Industry*, unpublished data report prepared for the Office of Energy Analysis, U.S. Energy Information Administration, Washington, DC, August 2012.

As noted previously, wet process capacity is assumed to retire linearly, without replacement, and the demand for associated raw grinding services is directly linked to wet process clinker production. Surviving baseline capacity is computed in subroutine Step Capacity, which is described starting on page 102.

The survival function determines the share of needed capacity added in a given year that survives to the current model year. An example is shown in in Figure 12 on page 104.

Then any needed added incremental capacity, stored and retained by model year, for the current model year is determined by both surviving baseline and surviving incrementally added capacity as follows:

$$Needed\_Capacity_y \ = \ Raw\_Material_y \ - \ Surviving\_Capacity_y \qquad\qquad (\,198\,)$$

$Needed\_Capacity_y$ and $Surviving\_Capacity_y$ are calculated in subroutine Step Capacity, which is described starting on page 102.

The use of the wet process is considered to be declining, and is consequently not subject to replacement by new, similar technologies. Because of different input process (for example, raw grinding) requirements associated with the wet process, it needs to be tracked separately, and retirements are accommodated by additions to dry process technology. Any added incremental capacities for dry rotary kilns are subsequently allocated to raw grinder.

As with the other nodes, needed capacity additions, yielding $Needed\_Capacity_y$ and $Surviving\_Capacity_y$ are calculated in subroutine Step Capacity, which is described starting on page 102. The annual market share for each new technology is calculated in subroutine Logit_Calc, which is described starting on page 104.

Process Emissions Calculations

Process emissions are significant during clinker production at cement manufacturers. IDM computes these process emissions as follows:

Process-related emissions are calculated using empirical relationships from the U.S. Environmental Protection Agency that link the emissions of CO2 (process-related) and cement kiln dust (CKD) with the amount of raw material entering the kiln. Process-related CO2 emissions are computed for each ton of clinker produced, while CKD emissions are calculated based on each ton of cement produced. Note that CKD emissions are typically recycled with a 2% loss.[45] A standard emissions factor (0.51 tons of carbon dioxide per ton of clinker) is used to calculate process-related CO2 emissions. When raw material additives, such as blast furnace slag, are used, the emissions factor drops to 0.50 tons of CO2 per ton of clinker.

Fuel-related CO2 emissions are calculated from the portfolio of fuels used by the cement industry over a given year. These emissions are calculated in the IDM and added to the amount of process-based CO2 emissions described above.

LIME INDUSTRY

The lime industry submodule calculates lime industry energy consumption. Cement and lime energy shipments and energy consumption are reported together, although they are projected separately. The MAM estimates lime shipments. The new process flow model calculates UEC as a function of capital equipment used and updates capital equipment based on demand, capacity surviving, and new capacity.

Capacity Determination
Lime production in 2014 represents existing baseline capacity to minimize the need for substantial new capacity based on the relatively low levels of demand (or production) for lime reported by the U.S.

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[45] Huntzinger et al, Life Cycle Analyses of Portland Cement Manufacture, J. of Cleaner Production, 17 (2009) pp. 668-675.

Geological Survey in 2008 as more representative of capacity than recession related capacity. Lime demand is subsequently allocated among the three competing types of kilns, per the inputs from the CIMS database. In the IDM base year, baseline capacity is equal to physical production:

$$Baseline\_Capacity\_IBYR = Demand\_IBYR \qquad\qquad (199)$$

where

| $Demand\_IBYR$ | = | Physical lime production reported by U.S. Department of Interior, U.S. Geological Survey, for 2014; and |
| $Baseline\_Capacity\_IBYR$ | = | Lime kiln capacity in 2014. |

For post-2014 years, the lime kiln capacity is determined from baseline retirements and computed as follows:

$$Baseline\_Capacity\_Lag = Baseline\_Capacity \qquad\qquad (200)$$

$$Baseline\_Capacity = Baseline\_Capacity\_Lag - \left[\frac{Baseline\_Capacity\_IBYR}{Baselife}\right] \qquad (201)$$

where

$Baseline\_Capacity\_Lag$	= Previous year's lime kiln capacity;
$Baseline\_Capacity$	= Surviving baseline kiln capacity;
$Baseline\_Capacity\_IBYR$	= Initial lime kiln capacity in 2014; and
$Baselife$	Lifetime of baseline lime kiln capacity, assumed to be 20 years.

The survival function determines the share of needed capacity added in a given year that survives to the current model year. An example is shown in in Figure 12 on page 104. As with the other nodes, surviving capacity and needed capacity additions, are calculated in subroutine Step Capacity, which is described starting on page 102.

Table 27 displays the initial share of baseline capacity of lime kilns, by fuel.

Table 27. Initial allocation of lime kilns

Type	Description	Initial share $Technology\_Share_{Type}$
Coal	Rotary kiln: coal	73%
Residual fuel oil	Rotary kiln: residual fuel oil	17%
Natural gas	Vertical shaft kiln: natural gas	10%

Source: SAIC, *Model Documentation Report: The U.S. Lime Industry*, unpublished data report prepared for the Office of Energy Analysis, U.S. Energy Information Administration, Washington, DC, August 2012.

In summary, each year following the base year incremental additions to kiln capacity are based on the following assumptions:

- Baseline capacity is retired at a linear rate over a fixed time frame.

- Production demand in excess of surviving baseline capacity will be met with replacement equipment.

- Equipment acquired after 2014 will retire according to a logistic decay function.

After establishing the required additions of kiln capacity, the model allocates the projected new capacity (*Incr_Adds $_y$*) among the competing technologies.

Capacity Allocation

New capacity is allocated among technologies using a multinomial logit model, in which the characteristics of competing alternatives are assessed. The annual market share for each new technology is calculated in subroutine Logit_Calc, which is described starting on page 104. Characteristics of lime kilns are extracted from the CIMS database, which contains detailed data for each type of lime kiln, by fuel type, and are shown in Table 28.

Table 28. Characteristics of lime kilns

Technology type	Total fixed costs	Technology attributes	
		Fuel use	Carbon dioxide emissions
	(dollars per kilotonne)	(million British thermal units per kilotonne)	(tons per kilotonne)
Coal	36,701	4,893	474.1
Residual Fuel Oil	34,752	5,632	431.9
Natural Gas	31,593	4,931	258.8

SAIC, Model Documentation Report: The U.S. Lime Industry, unpublished data report prepared for the Office of Energy Analysis, U.S. Energy Information Administration, Washington, DC, August 2012.

The energy projected and then reported in the IDM for lime production is based on the kiln output and energy of each type of kiln and other process and assembly end-use activities, as reported in the CIMS data and latest MECS data. Partitioning of national estimate of energy consumption in the lime industry into census regions occurs in the CALPATOT subroutine of IDM.

GLASS INDUSTRY

Glass is an inorganic product that is typically produced by melting a mixture of silica (sand, 75%), soda (around 15%), and a calcium compound (usually lime, 10%). To this are added the desired metallic oxides that serve as coloring agents. All industrial glass is manufactured through the following steps:

1. Preparing the right mix of raw materials
2. Melting and refining the raw materials
3. Forming and finishing the molten glass into desired products

The mix of raw materials depends on the type of glass being manufactured and its desired properties and color. Melting varies in scale, temperature, and residence time, and it is typically carried out in tank melters. Forming is much more diverse considering the wide range of products from the glass industry. Some glass products require additional finishing processes.

Products manufactured by the U.S. glass industry span a broad diversity, including food and beverage containers, flat glass, fiberglass insulation, windows for automobiles and buildings, video displays, cookware, leaded crystal, and light bulbs. In the glass submodule these products are classified under four general categories—flat glass, container glass, blown glass, and fiberglass (wool insulation and textile fiber). Blown glass (also known as specialty glass) is the smallest of the four glass industry segments. The large diversity of products is accompanied by an equally large diversity of forming processes. Table 29 shows the four categories of glass (by NAICS code) that are modeled.

Table 29. Major U.S. glass industry segments and typical products

Type of glass	North American Industry Classification System code	Description
Flat glass	327211	Sheet plate and float glass for residential and commercial construction, automotive applications, tabletops, and mirrors.
Container glass	327213	Packaging of foods, beverages, household chemicals, cosmetics, and pharmaceuticals.
Blown glass	327212	Pressed and blown glass for tableware, cookware, lighting, televisions, liquid crystal displays, laboratory equipment, and optical communications.
Fiberglass	327993	Fiberglass (glass wool) insulation for buildings, roofing, and panels.
	327212	Textile and plastic reinforcement fibers for the construction, transportation, and marine industries.

Source: U.S. Census Bureau

Figure 15 summarizes the glass submodule execution. The code is run for each year in the projection period. The glass industry shipments in dollars are determined by the MAM. These shipments are then assigned to the four glass segments (subroutine Glass Segment Shipping). The capacity requirement is estimated in metric tons for each glass segment. The capacity estimates include yearly estimates of both the remaining baseline capacity before the projection years and remaining new capacity added during the projection years, as well as the additional capacity required each year to meet demand. Flat glass and blown glass include finishing processes. All four glass segments have forming, furnace, and preparation processes. As new capacity is added for each process step in each glass segment, the technology is selected based on an evaluation of the relative economic benefit of the available technologies. An adjustment is made to fuel consumption for oxy-fuel furnaces (subroutine OxyFuel). The results are then reported.

Figure 15. Subroutine execution for the glass submodule
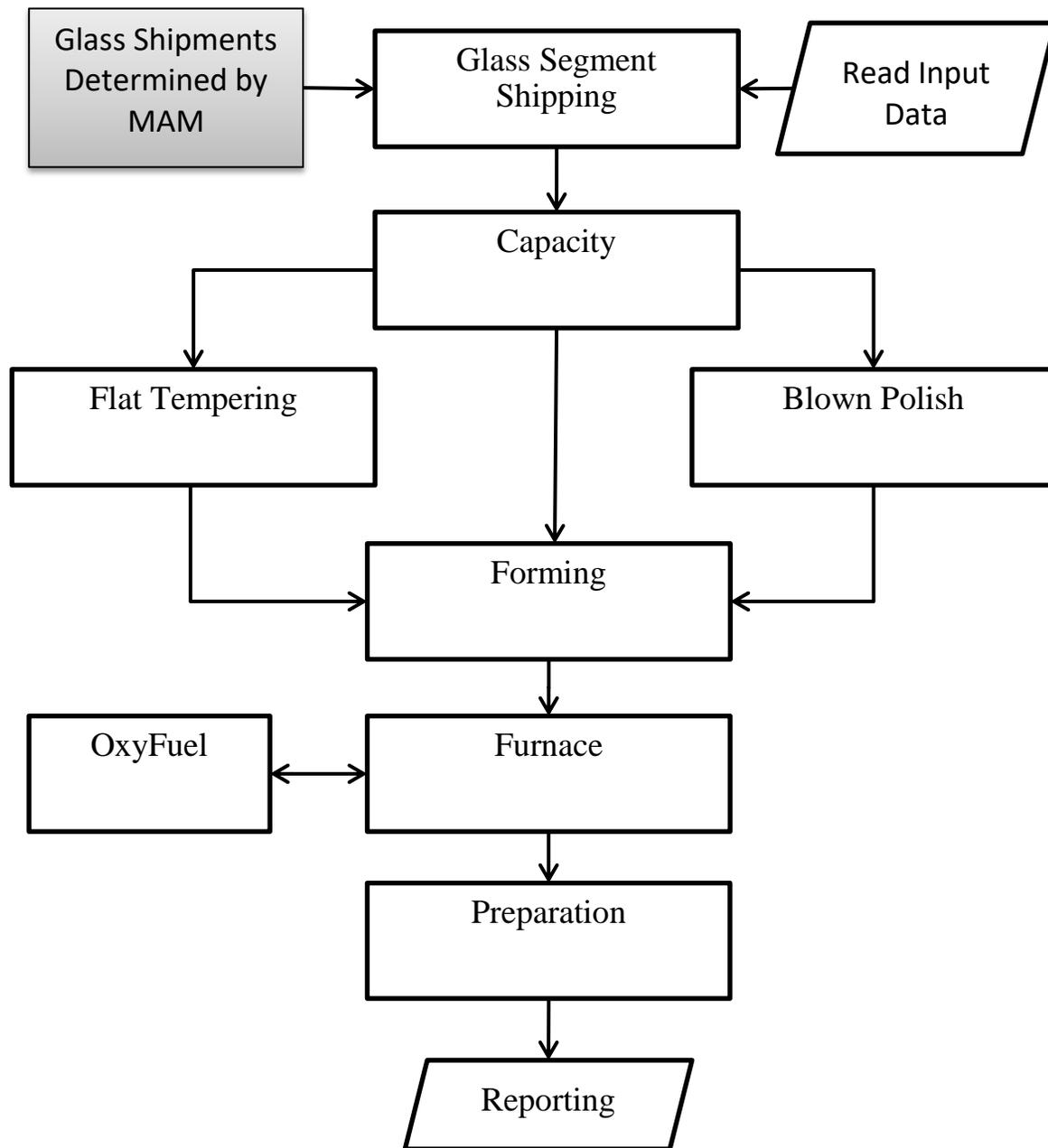
Source: U.S. Energy Information Administration

The algorithms used for the four glass segments are the same with variations in parameters. The available technologies also vary by glass segment and are described in the next section followed by a description of the algorithms.

Technology Choice Options

Table 30 through Table 33[46] show the technologies that the model may select for the four glass segments and process steps. The initial technology share is shown, based on detailed research of the CIMS data from 2006. These shares are assumed to persist to 2014. The technologies that are shown as 0% share are options for the replacement of retired capacity as are all of the listed technologies. The glass submodule only considers natural gas and electricity as fuels. The small amounts of other fuels used in glass production are based on the UEC/TPC data from MECS, which is outside of the glass submodule. All of the process steps shown in the figures below use electricity for various facilities support services. This electricity use is not part of the use of electricity as a fuel. In the case of the preparation process, the energy use is all electricity as part of services and not fuels. Even when the technology is the same among the four glass segments the parameters associated with the technology, such as energy intensity, vary by glass segment.

Table 30. Flat glass technology choice

Process step	Initial technology share	Energy source	
		Natural gas	Electricity
Preparation		NO	NO
Base_Tech_Preparation_FLAT_PGL	100%		
Preparation_w_Computer_Process_ctrl_FLAT_CPC	0%		
Furnaces			
Lg_Regenerative_Melters_FLAT_LRM	100%	YES	NO
Lg_Boosted_Regenerative_Melters_FLAT_LBRM	0%	YES	YES
Lg_Regenerative_Melters_w_Fluidized_Bed_Preheater	0%	YES	NO
M_Lg_Boosted_Regenerative_Melters_w_Fluidized_Bed_Preheater	0%	YES	YES
Advanced_Glass_Melter_FLAT_AGM	0%	YES	NO
Forming		YES	NO
Base_Tech_Form_Anneal_FLAT_FGL	80%		
Computer_Process_ctrl_Emhart_Type_540_Forehearth_FLAT_EM	20%		
Computer_Process_ctrl_Bh_F_High_Press_Gas_Fire_FLAT_BHF	0%		
Finishing		YES	NO
Tempering_Of_Flat_Glass	100%		
Tempering_Advanced	0%		

Source: U.S. Energy Information Administration

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[46] SAIC, "Draft Report on Modeling the Mass and Energy Flow in the Glass Industry for the NEM-IDM, June, 2011.

Table 31. Container glass technology choice

Process step	Initial technology share	Energy source	
		Natural gas	Electricity
Preparation		NO	NO
Base_Tech_Preparation_CONTA_PGL	100%		
Preparation_w_Computer_Process_ctrl_CONTA_CPC	0%		
Furnaces			
Lg_Regenerative_Melters_CONTA_LRM	20%	YES	NO
Lg_Boosted_Regenerative_Melters_CONTA_LBRM	30%	YES	YES
M_Lg_Regenerative_Melters_w_Fluidized_Bed_Preheater	50%	YES	NO
Rm_Lg_Boosted_Regenerative_Melters_w_Fluidized_Bed_Preheater	0%	YES	YES
Advanced_Glass_Melter_CONTA_AGM	0%	YES	NO
Sm_Fossil_Fuel_Fired_Melters_CONTA_FFM	0%	YES	NO
Electric_Melters_CONTA_EM	0%	NO	YES
Direct_Fired_Melters	0%	YES	NO
M_Fluidized_Bed_Sm_Fossil_Fuel_Fired_Melters_CONTA_FBFFM	0%	YES	NO
Fluidized_Bed_Electric_Melters_CONTA_FBEM	0%	NO	YES
Forming		**YES**	**NO**
Base_Tech_Form_Anneal_CONTA_FGL	50%		
Computer_Process_ctrl_Emhart_Type_540_Forehearth_CONTA_ET	0%		
Computer_Process_ctrl_Bh_F_High_Press_Gas_Fire_CONTA_BHF	50%		

Source: U.S. Energy Information Administration

Table 32. Blown glass technology choice

Process step	Initial technology share	Energy source	
		Natural gas	Electricity
Preparation		NO	NO
Base_Tech_Preparation_BL_PR_PGL	100%		
Preparation_w_Computer_Process_ctrl_BL_PR_CPC	0%		
Furnaces			
Sm_Fossil_Fuel_Fired_Melters_BL_PR_FFM	70%	YES	NO
Electric_Melters_BL_PR_EM	5%	NO	YES
M_Fluidized_Bed_Sm_Fossil_Fuel_Fired_Melters_BL_PR_FBFFM	25%	YES	NO
Fluidized_Bed_Electric_Melters_BL_PR_FBEM	0%	NO	YES
Advanced_Glass_Melter_BL_PR_AGM	0%	YES	NO
Forming		YES	NO
Base_Tech_Form_Anneal_BL_PR_FGL	100%		
Computer_Process_ctrl_Emhart_Type_540_Forehearth_BL_PR_ET	0%		
Computer_Process_ctrl_Bh_F_High_Press_Gas_Fire_BL_PR_BHF	0%		

Process step	Initial technology share	Energy source	
		Natural gas	Electricity
Finishing		YES	NO
Fire_Polishing_Of_Blown_And_Pressed_Glass	100%		
Advanced_Polishing	0%		

Source: U.S. Energy Information Administration

Table 33. Fiber glass technology choice

Process step	Initial technology share	Energy Source	
		Natural gas	Electricity
Preparation		*NO*	*NO*
Base_Tech_Preparation_FIBRE_PGL	100%		
Preparation_w_Computer_Process_ctrl_FIBRE_CPC	0%		
Furnaces			
Computer_Process_ctrl_Bh_F_High_Press_Gas_Fire_FIBRE_BHF	83%	*YES*	*NO*
Sm_Fossil_Fuel_Fired_Melters_FIBRE_FFM	7%	*YES*	*NO*
Electric_Melters_FIBRE_EM	10%	*NO*	*YES*
M_Fluidized_Bed_Sm_Fossil_Fuel_Fired_Melters_FIBRE_FBFFM	0%	*YES*	*NO*
Forming		*YES*	*NO*
Base_Tech_Form_Anneal_FIBRE_FGL	100%		
Advanced Forming and Finishing	0%		

Source: U.S. Energy Information Administration

Batch preparation

Batch preparation involves raw material selection and blending. The physical and chemical properties of the final glass product depend on the raw material composition, which in turn varies with each type of glass produced. Of particular interest for most applications is the chemical durability, transmission, softening point, and thermal expansion of the glass. Raw materials consist largely of glass-forming oxides that may be grouped into network formers (SiO_2, B_2O_3, P_2O_5), intermediate oxides (Al_2O_3, TiO_2, ZrO_2), and network modifiers (Na_2O, CaO, MgO).

A typical soda-lime glass composition used for window or container glass consists of approximately 60% silica sand, approximately 18% calcium monoxide from limestone, and approximately 20% sodium monoxide from soda ash. Other common ingredients are feldspar, salt cake, colorants, and refining agents (for example, arsenic, sodium chloride). Added to the mixture of raw materials to be ground is cullet. Cullet is waste or broken glass, which may be generated at the plant or obtained from the marketplace.

The use of clean cullet ranges from 5% to 25% by weight. In the case of colored container glass, more than 90% of cullet by weight is from the used glass market. During batch preparation, the fine-ground

raw materials are weighed according to the recipe and are subsequently mixed to achieve a homogenous composition. Cullet can be either mixed into the batch or charged into the glass-melting furnace (or tank) simultaneously with the batch.

Two preparation technologies are available for the four glass segments with variations in parameters. The Base_Tech_Preparation step is the currently used technology. The Preparation_w_Computer_Process_ctrl technology reduces the energy use through advanced process control technology.

Melting furnaces

The melting of glass, with the exception of a few blown glass manufacturing processes, is accomplished with continuously operating tank furnaces. Discontinuous glass melting processes operate as pot furnaces and day tanks. In pot furnaces, one or more refractory crucibles are filled with batch and cullet and placed in a natural gas-fired or electrically-heated furnace. After melting the batch, the temperature of the furnace is typically increased to lower the melt viscosity and activate refining agents to remove bubbles from the melt (refining) and then lowered to condition the glass for forming. Day-tanks are small tanks that are charged with batch and cullet. As in a pot furnace, the temperatures are adjusted for melting, refining, and conditioning of the glass melt.

A typical glass-melting tank consists of a batch charging area (the doghouse) attached to a refractory basin covered by a refractory superstructure (the crown). Presently, most glass furnaces in the United States are heated with natural gas. Common heating methods are air-fuel burners and, more recently, oxy-fuel burners. Some furnaces use direct electrical heating (Joule heating), in particular, for wool-type fiberglass production that provide more uniform temperature distributions compared with natural gas heaters. Combinations of both heating methods (electric boosting) is used to help melt the glass since glass is an electrical conductor at high temperatures. Electric boosting typically consists of 10-30% of the total energy demand, but increases production rates and the flexibility of the furnace operation.

Common to both flat and container industry segments are regenerative and recuperative furnaces. Fiberglass furnaces are generally smaller than container and flat glass furnaces. Pressed and blown glass (specialty glass) furnaces are the smallest. To improve energy efficiency and achieve higher flame temperatures, air-fuel furnaces typically recover heat from exhaust gas streams with regenerative systems to preheat the combustion air. In regenerative systems, the exhaust gases stream through large chambers packed with refractory bricks arranged in patterns forming open conduits.[47] A fluidized bed reactor is a type of reactor device that can be used to carry out a variety of multiphase chemical reactions where a fluid (gas or liquid) is passed through a granular solid material at high enough velocities to suspend the solid and cause it to behave as though it were a fluid. The Advanced Glass Melter is a projected technology based on the most energy-efficient current technologies.

Forming and conditioning

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[47] Worrell, Ernst, Christina Galitsky, et al., March 2008, <u>Energy Efficiency Improvement and Cost Savings Opportunities for the Glass Industry</u>, An Energy Star Guide for Energy and Plant Managers, Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-57335.

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After completion of the refining stage, the homogenous, bubble-free glass leaves the tank and enters the forehearth, sometimes through a specifically designed pathway (channel or throat). The main function of the forehearth is to condition the glass, that is, to deliver glass with the desired temperature and temperature distribution to the forming process. Any deviations from the desired thermal profile can cause undesirable differences in viscosity and subsequently lead to visible defects in the finished product. Forehearths can be natural gas-fired or electrically heated.

The conditioned glass is delivered from the forehearth to the forming equipment at a constant rate. Depending on the process, the viscous glass stream is either continuously shaped (float glass, fiberglass), or severed into portions of constant weight and shape, which are delivered to a forming machine (container glass). Advanced process control is also an energy efficiency technology considered. For some glass segments an advanced projected technology is based on the most energy-efficient current technologies.

Glass submodule algorithms

Each of the following sections describes the algorithms associated with the flat glass segment, which are the same as the algorithms for the other three glass segments. There are variations in parameters to account for differences in energy intensity, retirement rates, costs, etc. Different variable and parameter names associated with the four glass segments are distinguished with abbreviations for the glass segments. When a variable or parameter in the flat glass algorithms reviewed in the following sections has either flg or fg in the name, the algorithms for the other three glass segments have names with the following substitutions:

- ○ fgl, fg: Flat glass;
- ○ bgl, bg: Blown glass;
- ○ cgl, cg: Container glass; and
- ○ gpl, gp: Glass products such as fiberglass and textiles.

GL_Shipping Subroutine (Glass Segment Shipping)

The GL_Shipping subroutine applies to all of the glass segments. The shipment data from MAM is for the entire glass industry. The historical shipments for the four glass segments are based on historical shipment shares applied to historical shipment data for the glass industry. The projected shipment shares for the four glass segments are based on linking glass shipments by category to other industries that are correlated with glass shipments by glass segment, as follows:

$$\text{yfg}_y = 0.00171 * (\text{mc\_revind}_{mnumcr,33,y} + \text{mc\_revind}_{mnumcr,42,y}) - 0.1756 \qquad (202)$$

$$\text{ybg}_y = 0.048151 * .24 * mc\_revind_{nnumcr,7,y} + 2.932934 \qquad (203)$$

$$\text{ycg}_y = 0.003772 * mc\_revind_{nnumcr,1,y} + 2.533845 \qquad (204)$$

$$\text{ygp}_y = 0.070395 * mc\_revind_{nnumcr,23,y} - 2.77323 \qquad (205)$$

where

yfg_y = Flat glass shipments for the year y;

ybg_y = Blown glass shipments for the year;

ycg_y = Container glass shipments for the year;

ygp_y = Glass products such as fiberglass and textile shipments for year y;

$mnumcr$ = Aggregated census division for shipments; and

mc_revind = MAM macro variable that denotes gross output for Transportation Equipment (33), Construction (42), Textiles (7), Food (1), and Plastics (23).

The estimated shipments by glass segment are then summed to provide a total shipment for the glass industry. This total shipment is only used to estimate shares for the four glass segments. The shipment shares based on the estimated shipments are then applied to the total glass shipments from MAM to determine the shipments for the glass segments, as follows:

$$ytot_y = yfg_y + ybg_y + ycg_y + ygp_y \qquad\qquad (\,206\,)$$

$$GL\_fg\_ship_y = \frac{yfg}{ytot} * mc\_revind_{mnumcr,24,y} \qquad\qquad (\,207\,)$$

$$GL\_bg\_ship_y = \frac{ybg}{ytot} * mc\_revind_{mnumcr,24,y} \qquad\qquad (\,208\,)$$

$$GL\_cg\_ship_y = \frac{ycg}{ytot} * mc\_revind_{mnumcr,24,y} \qquad\qquad (\,209\,)$$

$$GL\_gp\_ship_y = \frac{ygp}{ytot} * mc\_revind_{mnumcr,24,y} \qquad\qquad (\,210\,)$$

where

$ytot_y$ = Total shipments estimated based on correlated industries for the year y;

$GL\_fg\_ship_y$ = Flat glass shipments for the year;

$GL\_bg\_ship_y$ = Blown glass shipments for the year;

$GL\_cg\_ship_y$ = Container glass shipments for the year;

$GL\_gp\_ship_y$ = Glass product shipments such as fiberglass and textiles for the year; and

$mc\_revind_{mnumcr,24,y}$ = Shipments for all census divisions (11), the overall glass industry (24), and for the year (y).

GL_Flatcap, GL_Contcap, GL_Blowncap, and GL_Fibercap Subroutines (Capacity Subroutimes for the Four Glass Segments)

When existing capacity is retired, it is then replaced with new capacity. The capacity subroutines estimate the needed capacity each year based on the retirement of both the starting baseline capacity

and the retirement of new capacity that is added over the projection years. The equations are from the GL_Flatcap subroutine associated with the flat glass sector, but they apply to all forms of glass.

The initial starting baseline capacity for the glass segments is an input based on historical data, which is then converted from short tons to metric tons. The survival function determines the share of needed capacity added in a previous year that survives to the current model year. An example is shown in Figure 12 on page 104. In addition to baseline capacity retirements and surviving capacity, needed capacity additions are calculated in subroutine Step Capacity, which is described starting on page 102.

Technology Shares and Energy Use for the Process Step

After the needed capacity is calculated for the current year, the technology shares are assigned to the needed capacity. Each of the process steps for each of the glass segments has the associated technologies assigned to the needed capacity. The algorithm is the same for all of the process steps for all four glass segments. The technology shares for each new technology are calculated in subroutine Logit_Calc, which is described starting on page 104.

dOXY_Fuel Subroutine

Modern glass furnace technology aims to increase the use of oxygen as a way to increase fuel efficiency and reduce emissions of nitrogen oxides (NOx). Consequently, oxygen is increasingly being used to replace air in combustion.

The shares for the use of oxygen are based on the percentage cost advantage (pca) that is estimated based on current-year fuel prices and the cost savings associated with reductions in natural gas associated with each furnace technology and each glass industry segment. This percentage cost advantage is then used in the following equation to estimate the oxygen fuel shares for each furnace. The first two parameters (1, 2) used in the equation are based on research of oxygen fuel limits. The other two parameters (3, 4) are used in the exponential equation to adjust the time frame in which oxygen fuel may be implemented. The estimated oxygen shares are then used to adjust both the natural gas and the electricity use for the associated furnace type by glass segment. The equations are as follows:

$$gl_{oshares_{nf}}$$

$$= gl\_OxyShrFac_1$$
$$+ \frac{\boldsymbol{gl}\_OxyShrFac_2 - \boldsymbol{gl}\_OxyShrFac_1}{1 + exp(-gl\_OxyShrFac_2 \; * \; (pca_{nf} - \; gl\_OxyShrFac_2 + 10))} \; (211)$$

where

gl_OxyShrFac$_{nf}$ = Oxygen fuel shares by furnace type and glass segment;

gl_OxyShrFac$_{\boldsymbol{k}}$ = Oxygen share factors for the base fuel share factor (1) of 0.2 and the maximum fuel share factor (2) of 0.75. The parameters (3, 4) for the exponent calculation adjust the rate at which oxygen fuel is implemented with the values of 0.1 (3) and 120.0 (4);

pca_{nf} = Cost advantage %; for furnace nf and

nf = Index of furnace number for glass segment.

ALUMINUM INDUSTRY

Figure 16 shows a detailed process flow diagram for aluminum manufacturing. Accurate modeling of this heterogeneous and complex industry requires an optimal model from the range of models that simulate this sector. These range from models that require very specific processing details to those that use macroscopic industry representations. In the IDM's modeling approach, the process is first broken down into several unit operations using process engineering techniques. The energy consumed by each unit operation and the corresponding mass flow of material (raw materials, intermediates, or final products) through that unit operation are calculated from the data. Their ratio supplies the UEC specific for that unit operation. The energy demands for processing the required mass of material through each unit operation are calculated and aggregated to provide the total energy consumption for the desired amount of the product(s). By virtue of its ability to calculate energy demands at the unit operation level, the aggregated estimate is a more accurate calculation of energy consumption compared with that from a global UEC. This approach is discussed in detail in the ensuing sections, starting with a description of the aluminum manufacturing process.

Figure 16. Aluminum industry process flow
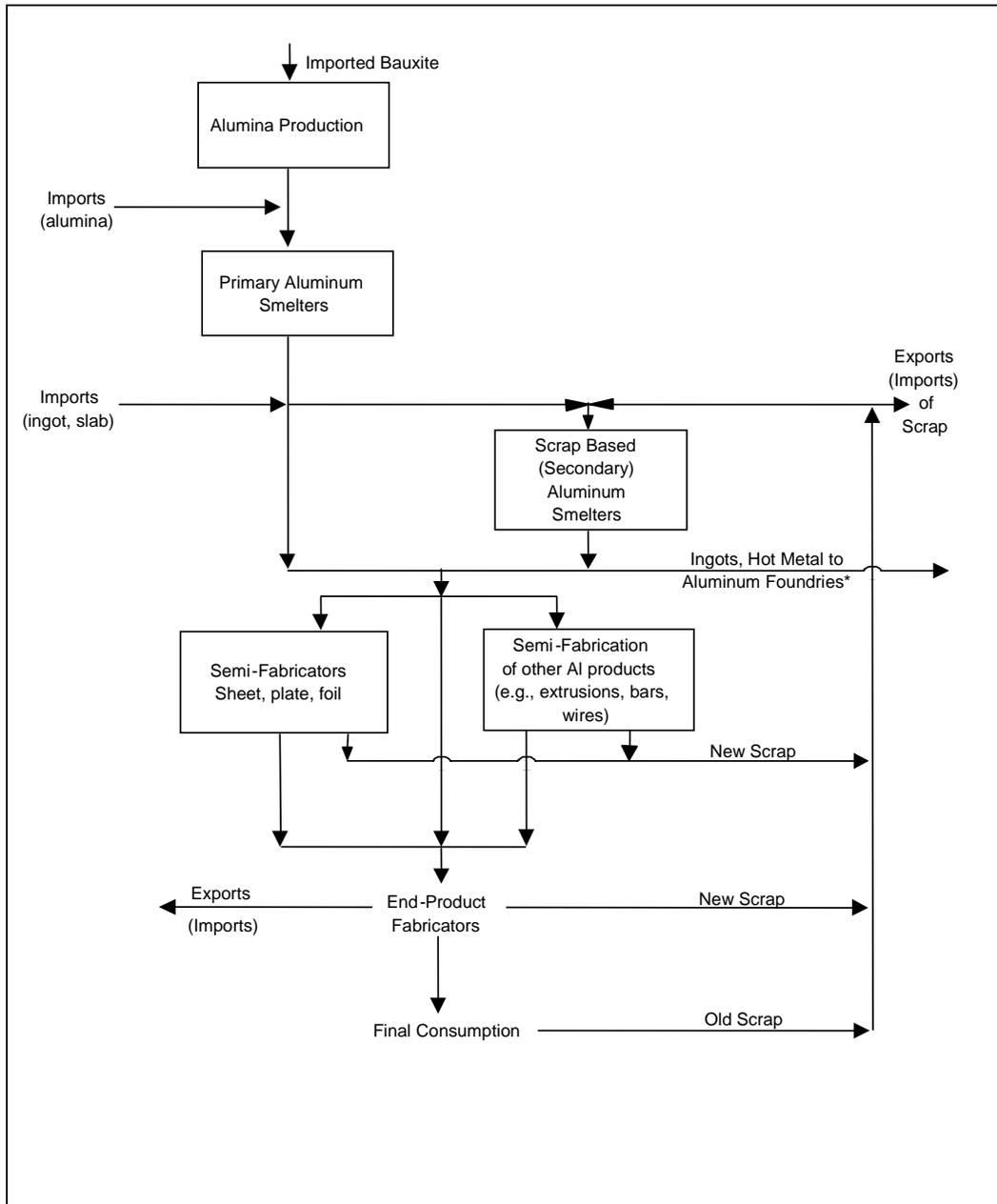
Source: U.S. Energy Information Administration

The U.S. aluminum industry consists of two major sectors: the primary aluminum sector, which uses alumina as raw material; and the secondary sector, which uses collected aluminum scrap as a raw material. The primary and secondary aluminum industries have historically catered to different markets, but these distinctions are fading. Traditionally, the primary industry bought little scrap and supplied wrought products, including sheet, plate, and foil. The secondary industry is scrap-based and has historically supplied foundries that produce die, permanent mold, and sand castings. More recently, secondary aluminum smelters have started supplying wrought (sheet) stock. In addition, in the past

decade, the primary producers have been moving aggressively into recycling aluminum, especially used beverage cans.

Figure 16 provides an overview of the process steps involved in the aluminum industry. The energy use analysis accounts for energy used in NAICS 3313, which includes the following:

- o Alumina Refining (NAICS 331311)
- o Primary Aluminum Production (NAICS 331312)
- o Secondary Smelting and Alloying of Aluminum (NAICS 331314)
- o Aluminum Sheet, Plate, Foil Manufacturing (NAICS 331315)
- o Aluminum semi-fabrication of products such as extrusions, tube, cable, and wire (found in NAICS 3316 and NAICS 331319)

Note: aluminum foundry castings (die-casting/permanent mold/other) are not considered as part of NAICS 331311.

Background on aluminum industry

The U.S. aluminum industry is a broadly diversified industry, starting with ore refining and ending with a wide variety of industrial and consumer products.[48] Aluminum (Al) is the third most abundant element in the earth's crust, but does not occur in nature as a metal, but only as an oxide (alumina), which in turn, is found in an ore called bauxite. In recent years, aluminum has begun to replace iron and steel in the automotive, electric power, and construction industries owing to its lighter weight, resistance to rust, alloy ability, and recyclability. It is popular as a packaging material for beverages and food containers, as well as household and institutional foil.

The supply of aluminum in the United States stems from three basic sources:

- o Primary production—domestic production from aluminum ore
- o Secondary production—domestic metal recovered from scrap, in other words, recycling
- o Imports—primary and secondary ingots and mill products

The end product from the first two sources is molten aluminum metal, which is not in a form suitable for marketing to potential end-users. Instead, ingot casting is the vital conduit between the molten metal and the manufacture of aluminum and aluminum alloy products. Extrusions, forgings, sheet, plate, and foil begin as billet and fabricating ingots. Sand, permanent mold, investment, and pressure die castings typically originate in alloyed re-melt ingots. For this modeling effort, aluminum imports are assumed to also be processed like primary and secondary aluminum into end-use products.

Currently there are more than 400 wrought aluminum and wrought aluminum alloys and more than 200 aluminum alloys in the form of castings and ingots to match the wide range of material characteristics

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[48] All bauxite for primary production is assumed to be imported to the United States.

required by end-use manufacturing processes.[49] In some cases, ingot formation and the manufacture of the final aluminum product for end-use applications are in the same location.

ALUMINUM_INDUSTRY Submodule: Subroutines

For this modeling effort, the boundaries established for the macroscopic modeling of the aluminum industry begin with the delivery of bauxite or scrap aluminum at the plant gate and end with ingot formation and the manufacture of aluminum sheet, plate, foil, and extruded products. Aluminum foundry operations for die and non-die casting are included.

The total energy consumed by the aluminum industry will be the sum of the energy consumed by the three modeled segments: primary aluminum production, secondary aluminum production, and product formation. Internal submodule calculations are in metric units, which are converted to English units for calculations external to this submodule.

Aluminum production

Aluminum production is defined as aluminum supply minus aluminum imports plus aluminum exports plus changes in stocks. These values are obtained exogenously from other NEMS modules or from the U.S. Geological Survey (USGS).

The output of the ALUMINUM_INDUSTRY submodule is the total quantity of aluminum shipments or Gross Output (in thousand metric tons) in a given year. A physical production index is derived as follows:

$$index2014 = \left[\frac{OUTIND_{13,11}}{ALUMIBYR}\right] \tag{212}$$

where

$\qquad index2014 =$ Index of Gross Output of aluminum shipments, projected for the aluminum industry;

$\qquad OUTIND_{13,11}$ =   Gross value of output for the aluminum industry (IDM industry code of 13) for the nation in the current projection year, as determined by NEMS MAM; and

$\qquad ALUMIBYR =$ Gross value of output for the aluminum industry for the nation in year 2014, as determined by MAM.

This index is used to project physical production using a forwarding indexing as follows:

$$domprod = domprod\_IBYR2 * index2014 \tag{213}$$

where

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[49] For aluminum specifications, see the Aluminum Association, http://www.aluminum.org/Content/NavigationMenu/TheIndustry/IndustryStandards/Teal_Sheets.pdf.

$domprod$	=	Physical output from the aluminum industry (IDM industry code of 13) for the nation in the current projection year, as determined by NEMS MAM and USGS statistics;
$index2014 =$	=	Index of physical quantity of aluminum shipments, projected for the aluminum industry; and
$domprod\_IBYR2 =$	=	Physical output for the aluminum industry (IDM industry code of 13) for the nation in 2014, based on USGS statistics.

A further refinement of the IDM allows separation of physical aluminum production into the primary and secondary production industries as follows:

$$AL\_primary\_prod_y = domprod * primprod\_percent_y \qquad (214)$$

where

$AL\_primary\_prod$	=	Physical output using primary production from the aluminum industry (IDM industry code of 13) for the nation in the current projection year, as determined by NEMS MAM and USGS statistics;
$domprod$	=	Physical output from the aluminum industry (IDM industry code of 13) for the nation in the current projection year, as determined by NEMS MAM and USGS statistics; and
$primprod\_percent_y$	=	Percentage of primary production of aluminum industry (IDM industry code of 13) for the nation in the current projection year y, as determined by regressions of endogenous NEMS variables related to fuel prices and USGS production statistics.

The IDM also assumes there is no new primary production capacity greater than surviving primary baseline capacity levels during the projection years, although idled primary capacity can be brought back into production. Secondary production capacity will be increased to meet the macroeconomic outputs prescribed in other modules of NEMS.

For each year following the base year (that is, 2014), incremental additions to primary aluminum capacity are based on the following assumptions:

- o Baseline capacity is retired at a linear rate over a fixed time frame (initially set to 20 years);
- o Production demand in excess of surviving baseline capacity will be met with idled equipment; and
- o Equipment acquired after 2014 will retire according to a logistic function.

Primary aluminum baseline capacity that survives is computed as shown on page 103.

Primary and secondary production shares

In the past few years, the share of secondary U.S. aluminum production increased above its historical share to nearly 80% of total aluminum output. This appears to be a permanent condition.[50] As a result, secondary aluminum production throughout the projection has been is constrained to be no less than 75% of total U.S. production.

AL_PRIM_SMELT

Primary aluminum production in 2014 represents existing baseline capacity, which is allocated among competing technologies based on either historical data or CIMS data implemented in the AL_SMELT_ALLOC subroutine as follows:

$$AL\_baseline\_capacity = baseline\_capacity\_IBYR \hspace{3cm} (\ 215\ )$$

where

$AL\_baseline\_capacity$ = Initial baseline capacity; and

$baseline\_capacity\_IBYR$ = Quantity of primary production output in 2014, in thousands of metric tons.

For each year following the base year (that is, 2014), incremental additions to primary aluminum production capacity are based on the following assumptions:

- o Baseline capacity is retired at a linear rate over a fixed time frame (initially set to 20 years);

- o Production demand in excess of surviving baseline capacity will be met with replacement equipment that survives for 30 years; and

- o Equipment acquired after 2014 will retire according to a logistic function that has a survival cap of 30 years.

The survival function determines the share of needed capacity added in a given year that survives to the current model year. An example is shown in in Figure 12 on page 104. Baseline capacity retirements, surviving capacity, and needed capacity are calculated in subroutine Step Capacity, which is described starting on page 102.

AL_SMELT_ALLOC

The technology shares of the two primary production technologies, as shown in Table 34, are derived based on logistic function of total installation costs, O&M costs, and environmental considerations. Table 34 presents the two existing aluminum electrolysis technologies based on anode configurations.

Table 34. Aluminum electrolysis technologies using Hall-Héroult process

Type	$TechShrSM_{Type}$

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[50] Skelton, Matthew, "U.S. Primary Aluminum Production Remains Low despite Slow Increase in Prices," *Today in Energy*, (Washington, DC: September 12, 2017) https://www.eia.gov/todayinenergy/detail.php?id=32872

Prebake	73%
Söderberg	27%

Source: Consolidated Impacts Modeling System database.

Electrolytic reduction cells differ in the form and configuration of their carbon anodes and alumina feed systems. They belong to one of four types:

- o Centre-Worked Prebake (CWPB)
- o Side-Worked Prebake (SWPB)
- o Horizontal Stud Söderberg (HSS)
- o Vertical Stud Söderberg (VSS)

Although four types exist today, the CIMS database only provides for two general electrolytic processes shares in current use. It is assumed that the Söderberg technology is no longer used for new capacity. Technology choices for the projection years based on CIMS include the following:

- o Side-Worked Prebake with standard controls
- o Side-Worked Prebake with point feeder controls
- o Centre-Worked Prebake with point feeder controls
- o Centre-Worked Prebake with point feeder controls and also with computer monitoring and automation
- o Inert anode with wetted cathode

Remaining ALUMINUM_INDUSTRY Submodule Subroutines

For the remaining subroutines that make up the ALUMINUM_INDUSTRY submodule, similar computations on capacity and allocation by technology diffusion are completed in subroutines AL_ANODE_PRD (that is, anode production), AL_PRIM_ALUMINA (that is, alumina production), AL_ALLOC (that is, alumina allocations), AL_SEC_PRD (that is, secondary production), and AL_SEC_ALLOC (that is, secondary technology allocation). Outputs from these routines—for example, respective projected production levels by technology—are linked with the technology-specific energy demands from the CIMS database to allow computation and reporting of energy consumption in the aluminum industry.

Influence of purchased electricity price on aluminum production

In addition to the process flow model described above, the IDM also incorporates a regression-based modifier to allow the purchased electricity price to help drive the choice between primary or secondary production. Primary production involves electrochemical smelting of alumina and is very electricity-intensive as compared with the more natural gas-intensive secondary (recycled) aluminum production, and so the industrial purchased electricity price can play a role in the production pathways choice. A regression was performed with historical primary: secondary ratio against industrial purchased electricity prices (both current and lagged), as follows:

$$ALRATIO_r = PCRX_{r,f=2} * ALSLOPE_r + PCRXLAG_{r,f=2} * ALSLOPELAG_r + ALINTERCEPT_r \quad (216)$$

where

$PCRX_{r,f} =$ the industrial purchased electricity price (*f=2*), by region *r;*

$PCRXLAG_{r,f} =$ the lagged (current year – 1) industrial purchased electricity price (*f=2*);

$ALSLOPE_r =$ slope regression parameter, by region *r;* and

$ALSLOPELAG_r =$ intercept regression parameter, by region *r.*

The adjusted primary and secondary production throughputs are then re-adjusted as follows:

$$PRODFLOW_{primary,r} = ALRATIO_r * ALPRODFLOWTOTAL_r \quad\quad\quad (217)$$

$$PRODFLOW_{secondary,r} = ALPRODFLOWTOTAL_r - PRODFLOW_{primary,r} \quad\quad (218)$$

The regression parameters were developed based on historical USGS data through year 1996 to 2010 (based on unpublished data from the U.S. Bureau of Mines and the U.S. Geological Survey–Minerals Yearbook and its predecessor, Mineral Resources of the United States) and are displayed in Table 35:

Table 35. Regression parameters for primary and secondary aluminum production projections

	Region 1	Region 2	Region 3	Region 4
Alslope	-0.000199	-0.000856	0.000324	-0.00227
Alslopelag	-0.000193	0.001498	-0.00142	-0.000394
alintercept	0.5645	0.10153	0.99405	2.1385

Source: U.S. Energy Information Administration

The multiple variable regressions provided for the four regions resulted in squared multiple correlations R^2 of 0.63, 0.49, 0.83 and 0.89 for regions 1 through 4, respectively. Although the coefficients for regions 1 and 2 are weak, the region with by far the most aluminum output, region 3, had a good R^2. Moreover, in all regions except region 1 (which accounts for only 15% of total U.S. aluminum output) there was at least one slope variable (Alslope or ALsloplag) with a statistical significance of 90% ($p < 0.1$). While a formal Dickey-Fuller test was not performed, inspection of plots of the first-differences of the dependent variables indicated sufficient stationary behavior.

Additional technical choice subroutines common to the iron and steel and paper industries

In addition to using Tech_Step and its associated subroutines, which described starting on page 102, the iron and steel industries and the paper industry models share two common technical choice subroutines:

XX_PRODCUR_Breakout: computes the PRODCUR matrix, total production needed to meet demand for each process step. This will differ by industry. IS_PRODCUR_Breakout computes the PRODCUR matrix for the iron and steel industry and PP_PRODCUR_Breakout computes the PRODCUR matrix for the paper industry.

XXSteam: computes steam demand and CHP use. Subroutine IS_Steam computes steam demand for the iron and steel industry and subroutine PPSteam computes steam demand for the pulp and paper industry.

Subroutine IS_PRODCUR_Breakout

The Iron and Steel Model separately addresses material flows through each of a series of component steps. These steps represent the intermediate (and occasionally competing) processes that are required to produce the volume of steel output projected by the MAM. As described in the IDM documentation, this is represented by an input-output model of the form that follows:

$$(I - PRODFLOW) * PRODCUR = d \qquad\qquad (\ 219\ )$$

Solving for $PRODCUR$ yields the following:

$$PRODCUR = (I - PRODFLOW)^{-1} * d \qquad\qquad (\ 220\ )$$

where

$PRODFLOW$	=	Input/Output coefficient matrix with final demand as the first column and the production steps as the other columns. The coefficients are the values in the *PRODFLOW* array;
I	=	Identity matrix;
d	=	Final demand vector, where the first element (d_1) is equivalent to PRODX (calculation details starting on page, and the remaining elements are zero; and
$PRODCUR$	=	Matrix of productive capacity needed to meet the final demand.

In the legacy approach, there are two $PRODFLOW$ matrices, corresponding to old and new technologies. These matrices remain static and are used, in conjunction with capacity retirement rates for each producing step, to model the evolution of the industry.

The current approach models this evolution by dynamically changing the elements of a single $PRODFLOW$ matrix, capturing industrial evolution through incremental adjustments of the $PRODFLOW$ elements. The $PRODFLOW$ matrix is an array of elements that indicate the output of predecessor steps required to produce one unit (that is, tonne) of output from the current step.

The PRODCUR calculation produces estimates of material flow for seven process steps and four census regions. The P&P model requires the flows to be aggregated into national totals, and then broken out

into sub-steps that will be used as inputs to the technology choice models, below. In its simplest form, the aggregated total is expressed as follows:

$$SumProdCur_{j,y} = \sum_{r=1}^{4} prodcur_{j,r,y} \qquad\qquad (221)$$

where

$SumProdCur_{j,y}$ =   Total U.S. production required to meet demand for process step j and year y, calculated above as a breakout of the $PRODCUR$ components, summed across regions; and

$prodcur_{j,r,y}$ =   regional element of PRODCUR matrix for step j Details of its calculation are on page 135.

IRON AND STEEL INDUSTRY

Iron and Steel Model Flow

The Iron and Steel (I&S) Model, like other energy-intensive industry models, is based on estimated flows of material across several process steps to ultimately meet final demand projections generated by the MAM. The basic flows are depicted below:

Figure 17. Detailed Iron and Steel Model flow
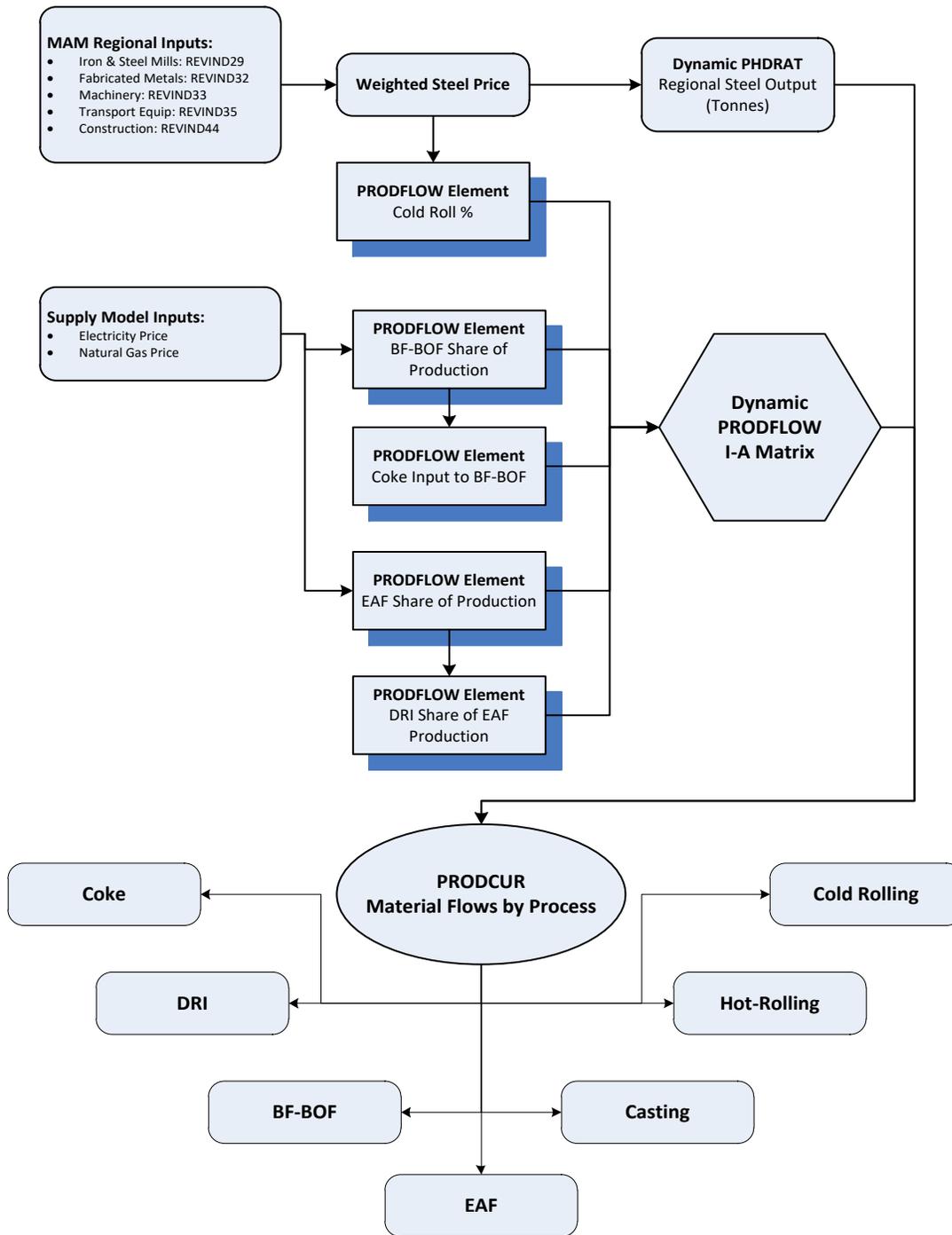
Source: U.S. Energy Information Administration

The MAM provides estimates of the value of steel produced, and the I&S model converts these figures into tonnes of material flows through the various process steps. The model uses a conversion factor (PHDRAT) to translate dollars of output to volume of production (PRODX).

Table 36. Iron and steel processes and technologies

Iron and Steel Step/PRODCUR element	*Total processes*	*Technology choice?*	*PRODCUR step index (IS)*
Hot rolling	3	Yes	1
Cold rolling	3	No	2
Continuous casting	3	Yes	3
Blast furnace or basic oxygen furnace	1	Yes	4
Electric arc furnace	1	Yes	5
Direct reduced iron	2	Yes	6
Coke production	1	No	7

Source: U.S. Energy Information Administration

Table 37. (I −PRODFLOW) matrix example for region 1 in 2014

(Steps/IS)		PRODX	Hot rolling	Cold rolling	Continuous casting	BF/BOF	EAF	DRI	Coke
		1	0	0	0	0	0	0	0
Hot roll	1	-1.047	1	0	0	0	0	0	0
Cold roll	2	**-0.451**	0	1	0	0	0	0	0
Continuous casting	3	0	-0.954	0	1	0	0	0	0
BF/BOF	4	0	0	0	**-0.310**	1	0	0	0
EAF	5	0	0	0	**-0.754**	0	1	0	0
DRI	6	0	0	0	0	**0.000**	**0.000**	1	0
Coke	7	0	0	0	0	**-0.983**	0	0	1

Source: U.S. Energy Information Administration

This example suggests that for every tonne of steel produced in this region, 1.047 tonnes of material has passed through the hot rolling step and 0.451 tonnes through the cold rolling step. In the legacy model, all of these coefficients are held constant; in the current model, the bolded coefficients are subject to change, based on economic conditions and assumptions about trends in the direction of manufacturing technologies.

To reiterate, the variable PRODCUR represents the flows of material (on a regional basis), in kilotonnes, through each of the seven process steps depicted above. The legacy model treated these elements as components of final demand, and calculated energy consumption for each step through the application of unit energy consumption (UEC) factors derived from MECS. The current model uses these process flows as inputs to subprocesses, in which the choice of technology will determine the consequent demand for energy. This process is done on a national, rather than a regional level. Accordingly, the PRODCUR element for specific steps is summed across regions and then is broken out into sub-flows for the purpose of the model.

Table 38. General (I - PRODFLOW) matrix for Iron and Steel Model

	PROD X	Hot rolling	Cold rolling	Continuous casting	BF/BOF	EAF	DRI	Coke
PRODX	1	0	0	0	0	0	0	0
Hot rolling	-a	1	0	0	0	0	0	0
Cold rolling	-b	0	1	0	0	0	0	0
Continuous casting	0	-c	0	1	0	0	0	0
BF/BOF	0	0	0	-d	1	0	0	0
EAF	0	0	0	-e	0	1	0	0
DRI	0	0	0	0	-h	-m	1	0
Coke	0	0	0	0	-k	0	0	1

Inverting the above matrix and multiplying terms provides the necessary output for each step of the production process gives the following:

$$prodcur_{r,y} = PRODX_{r,y} \qquad (222)$$

$$qHotRoll_{r,y} = a * PRODX_{r,y} \qquad (223)$$

$$qColdRoll_{r,y} = b * PRODX_{r,y} \qquad (224)$$

$$qContinuousCasting_{r,y} = (ac) * PRODX_{r,y} \qquad (225)$$

$$qBF\_BOF_{r,y} = (acd) * PRODX_{r,y} \qquad (226)$$

$$qEAF_{r,y} = (ace) * PRODX_{r,y} \qquad (227)$$

$$qDRI_{r,y} = [ac(dh + hm)] * PRODX_{r,y} \qquad (228)$$

$$qCoke_{r,y} = (acdk) * PRODX_{r,y} \qquad (229)$$

where

$prodcur_{r,y}$	=	total steel material flow;
$qHotRoll_{r,y}$	=	$prodcur_{is=1,r,y}$ quantity of hot rolling material flow needed to meet steel demand;
$qColdRoll_{r,y}$	=	$prodcur_{is=2,r,y}$ quantity of cold rolling material flow needed to meet steel demand;
$qContinuousCasting_{r,y}$	=	$prodcur_{is=3,r,y}$ quantity of continuous casting material flow needed to meet steel demand;
$qBF/BOF_{r,y}$	=	$prodcur_{is=4,r,y}$ quantity of Blast Furnace/Basic Oxygen Furnace (BF/BOF) material flow needed to meet steel demand;
$qEAF_{r,y}$	=	$prodcur_{is=5,,r,y}$ quantity of electric arc furnace material flow (EAF) needed to meet steel demand;

$$qDRI_{r,y} \qquad\qquad = \quad prodcur_{is=6,r,y}\text{quantity of Direct Reduced Iron (DRI) material flow}$$
needed to meet steel demand;

$$qCoke_{r,y} \qquad\qquad = \quad prodcur_{is=7,r,y}\text{quantity of coking material flow needed to meet steel}$$
demand; and

$$PRODX_{r,y} \qquad\qquad = \quad \text{final physical steel demand for region } r \text{ and year}$$

$$a, b, c, d, e, h, k, m \qquad = \quad \text{elements of } (\mathbf{I} - \mathbf{A})^{-1}$$

The PHDRAT and the PRODFLOW matrices are used to obtain regional process flows through each step (PRODCUR). The regional flows are summed to a national total, and each process step (EAF, DRI, cold roll, etc.) is represented by a national-level technology choice model. Total resulting fuel demand for each process step is then allocated back to the four regions based on their respective shares of national material flow.

For example, national hot rolling material flow needed to meet annual demand is obtained from summing up the regional material flows across the four census regions, as follows:

$$SumProdCur_{is=1,y} = \sum_{r=1}^{4} prodcur_{r,y} \qquad\qquad\qquad (\,230\,)$$

where

$SumProdCur_{is=1,y}$ national hot rolling output.

For each of the process steps described below, there are two sets of calculations. First, the existing capacity to meet demand is calculated, and, if this capacity is insufficient, incremental needed capacity is calculated and added. Second, added productive capacity is allocated among competing technology choices, based on a logistic model that is a function of the competing technologies' attributes.

Capacity Allocation Iron & Steel Manufacturing Processes:

The following sections describe the individual manufacturing processes addressed by the Iron and Steel Model. Each set of technology attributes is derived from the CIMS dataset. In some instances, the technology choice model considers a truncated subset of technologies, due to close similarity of costs and unit energy demands. Seven process steps are described in the order presented in PRODCUR, beginning with the final output of steel components and ending with the requirement for coke production.

Hot Rolling: IS = 1

The hot rolling step takes raw steel forms from the casting process (blooms, billets, and slabs), reheats them, and produces various structural products such as tubes, bars, and rods. The figure below depicts

the flows of material through the hot rolling step.

Figure 18. Hot rolling process step
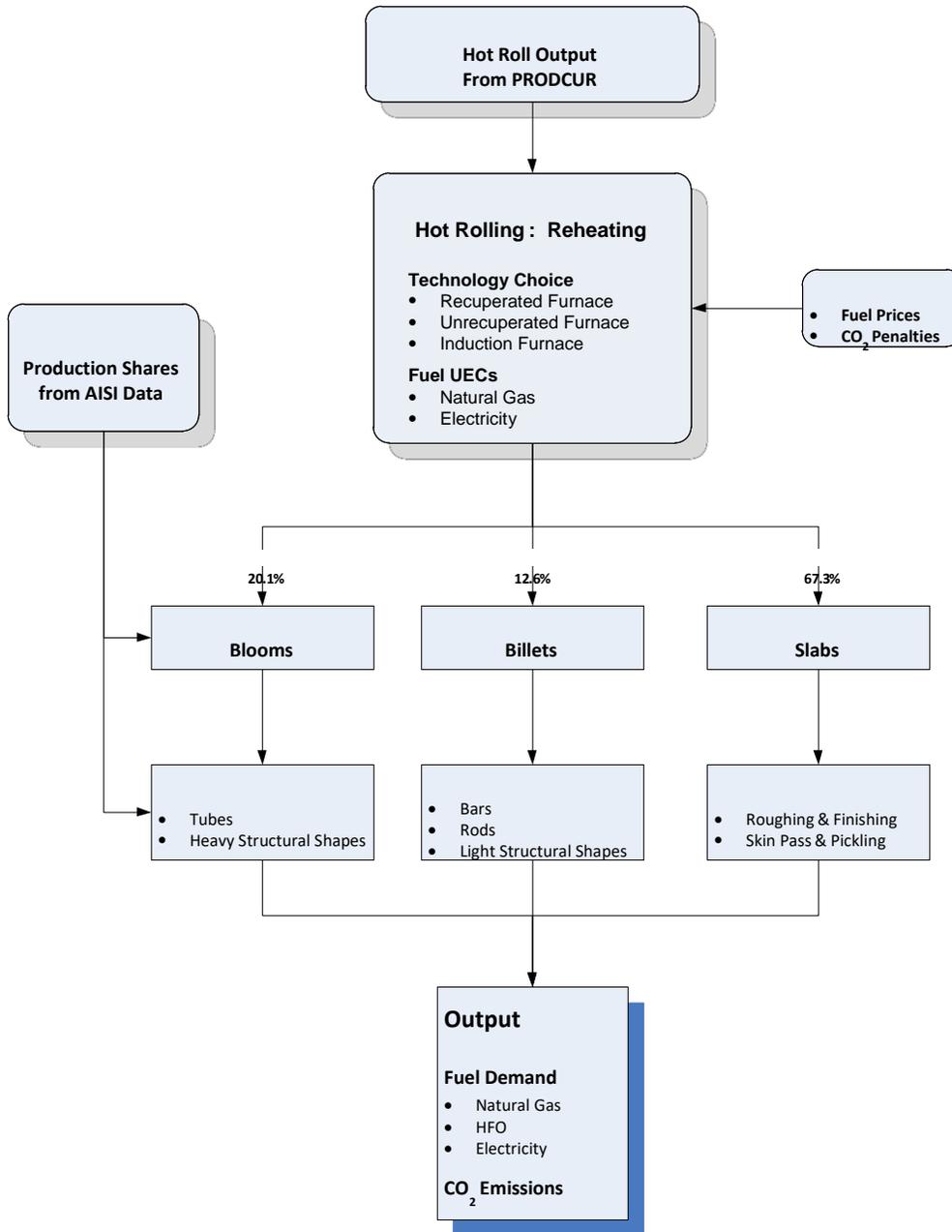
Source: U.S. Energy Information Administration

The process flow of steel is associated with three intermediate forms obtained from the casting subprocess: blooms, billets, and slabs. These forms are allocated according to estimates published by the American Iron & Steel Institute (AISI) for 2012. Baseline technology shares are shown in Table 39.

Table 39. Reheating baseline technology shares and attributes

Technology	Technology share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)
Recuperated reheating furnace	0%	3,054	1,686	0	88
Unrecuperated reheating furnace	40%	2,697	2,622	0	138
Induction reheating furnace	60%	9,675	512	124	27

Source: U.S. Energy Information Administration

The first stage of this step is determine the material flow for all subprocesses. The variable $SumProdCur_{IS=1,y}$ is calculated by summing regional material flows. An example is found on page 140. Once national output is known, subroutine Step_Capacity on page 102 determines how much, if any, capacity needs to be added. Technologies will be chosen for added capacity, (see subroutine Logit_Calc on page 104).

For the hot rolling step, only the reheating subprocess uses endogenous technology choice. Technology shares for blooms, billets and slabs are user-determined.

For the reheating subprocess, the fuel demand by technology, fuel, and year is given as follows:

$Energy\_Use_{IS=1,Tech,f,y}$

$$= Tot\_Prod\_Tech_{IS=1,Tech,y} * Fuel\_Use_{IS=1,Tech,f,y} \qquad (231)$$

where

$Energy\_Use_{IS=1,Tech,,f,y}$ = Total energy use, in MMBtu, for each technology.

$Fuel\_Use_{IS=1,Tech,f,y}$ = Energy intensity of reheating furnaces, in MMBtu/kilotonne, by fuel f and technology Tech;

$Tot\_Prod\_Tech_{IS=1,Tech,y}$ = Total material flow, in kilotonnes for each technology; and

After reheating, the steel is cast into forms. The material flow for each form is calculated as follows:

$$Form\_Flow_{IS=1,i,y} = SumProdCur_{IS=1,y} * FormShares_{IS=1,i} \qquad (232)$$

where

$Form\_Flow_{IS=1,i,y}$ = Tonnes of production for form $i \in [1,3]$; and

$FormShares_{IS=1,i}$ = Allocation shares, from 2012 estimates of the American Iron & Steel Institute, currently held static.

Table 40. Production shares for casting forms in 2012

Blooms	Billets	Slabs
20.1%	12.6%	67.3%

Source: U.S. Energy Information Administration

The forms are used to produce different structural products. For blooms, the primary products are tubes and heavy structural shapes. For billets, the products are bars, rods, and light structural shapes. The initial allocation of billets and slabs to products is based on AISI data for 2012. A final share can be set by the user based on analyst judgment. Shares in subsequent year change linearly between the initial and final shares.

The energy requirement for blooms or billets is given as follows:

$$Energy\_Use_{IS=1,i,f,y}$$

$$= \sum_{Prod} Form\_Flow_{IS=1,i,y} * Prod\_Share_{IS=1,i,y,Prod} * Fuel\_Use_{IS=1,i,f,Prod} \qquad (\,233\,)$$

where

$Prod\_Share_{Prod}$ = Allocation share of products Prod associated with form $i \in [1,3]$.

$Fuel\_Use_{f,Prod}$ = Fuel f unit energy consumption for the associated product, in million British thermal units (MMBtu) per kilotonne (kT). For slabs, the only fuel used is electricity.

Table 41. Technology shares and attributes for hot roll process

		Initial process share (2014)	Final process share (2050)	Natural gas (million British thermal units per kilotonne)	Heavy fuel oil (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)
Blooms							
	Tubes	50%	20%	6534	65	1314	0.3542
	Heavy structural shapes	50%	80%	2722	27	593	0.1473
Billets							
	Bars	33%	45%	2065	20	844	0.1117
	Rods	33%	45%	2178	22	1125	0.1181
	Light structural shapes	33%	10%	2065	20	677	0.1117

Source: U.S. Energy Information Administration

For slabs, the approach is slightly different. All slabs go through three subsequent processes: roughing, finishing, and either the skin-pass or pickling process, and each process has more than one technology. The electricity only energy requirement is given as follows:

$$Energy\_Use_{IS=1,i=3,f,y}$$

$$= \sum_{Prod=1}^{3} Form\_Flow_{IS=1,i=3,y} * Prod\_Share_{IS=1,i,y,Prod}$$

$$* \left(\sum_{Tech=1}^{2} Proc\_Share_{IS=1,i,y,Prod,Tech} * Fuel\_Use_{IS=1,i,f,Prod,Tech} \right) \quad (234)$$

Table 42. Slab finishing product process shares and energy intensity

Hot rolled products	Initial process share (2014)	Final process share (2050)	Electricity (million British thermal units per kilotonne)
Roughing (Proc = 1)			
Tech_1	20%	20%	194
Tech_2	80%	80%	117
Finishing (Proc = 2)			
Tech_1	80%	80%	328
Tech_2	20%	20%	285
Other (Proc = 3)			
Skin-pass	12%	12%	27
pickling	88%	88%	67

Source: U.S. Energy Information Administration

Summing across technologies provides the total demand by fuel for the hot rolling process, as follows:

$$Tot\_Energy\_Use_{IS=1,f,y} = \sum_{Tech} Energy\_Use_{IS=1,Reheat,Tech,f,y} + \sum_{i=1}^{2} Energy\_Use_{IS=1,i,f,y} \quad (235)$$

where

$Tot\_Energy\_Use_{IS=1.f,y}$ = Total energy demand, by fuel type fuel f, for the Hot Rolling step IS=1, in MMBtu;

$Energy\_Use_{IS=1,Hotroll,Tech,f,y}$ = energy use for hot rolling, defined on page 144;

$Energy\_Use_{IS=1,i,f,y}$ = energy use for blooms, billets, and slabs defined above; and

i = index of forms-billets, blooms, and slabs $i \in [1,3]$. Note that slab production ($i = 3$), only uses electricity.

Cold Rolling: IS = 2

In contrast to other steps in this model, cold rolling does not require any technology choice. The material flows generated by the PRODFLOW routine pass through the reduction step and several other sub-steps, allocated according to AISI data. The shares of cold-rolled steel going through these processes are currently held static. The figure below depicts the material flows.

Regional PRODCUR estimates are first summed to provide a national total of cold-rolled steel production, $SumProdCur_{IS=2,y}$.

Cold-rolled still proceeds through several sub-steps: reduction, then galvanizing or electrocleaning. There is one galvanizing process and three alternative electrocleaning processes.

Cold Roll Reduction: ISX = 1

The reduction step has two alternative technologies, which held at the same levels throughout the projection.

Table 43. Cold roll technology share and energy consumption characteristics

	Process share	Natural gas (million British thermal units per kilotonne)	Heavy fuel oil (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)
Cold roll reduction (natural gas)	95%	986	0	777	52
Cold roll reduction (oil)	5%	0	948	777	73

Source: U.S. Energy Information Administration

The energy demand for this step is calculated as follows:

$$Energy\_Use_{IS=2,IX=1,f,y}$$
$$= \sum_{Proc=1}^{2} SumProdCur_{IS=2,y} * Proc\_Shr_{Proc,IX=1} * Fuel\_Use_{Proc,f,IX=1} \quad (236)$$

where

$Proc\_Shr_{Proc,ISX=1}$ = Process share of technology of alternatives Proc (Natural Gas vs. Oil) and technology ISX=1; and

$Fuel\_Use_{Proc,f,ISX=1}$ = Unit energy consumption of fuel f for a given process, in MMBtu/kT.

Figure 19. Cold roll technology model flow
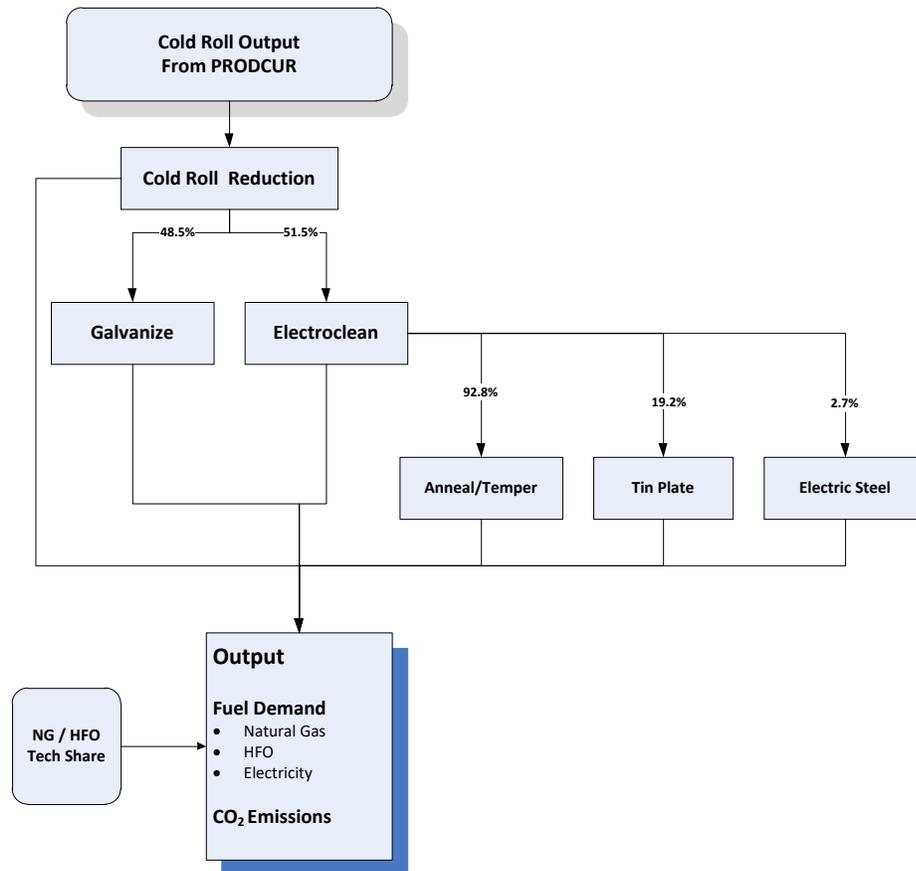
Source: U.S. Energy Information Administration

Galvanizing: IX = 2

The amount of steel to pass to the galvanizing stage is held fixed at 2014 levels.

Table 44. Galvanizing (technology and energy)

	Process share	Natural_gas (million British thermal units per kilotonne)	Heavy fuel oil (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)
Galvanize (natural gas)	96%	773	0.00	552	41
Galvanize (oil)	4%	0.00	721	552	55

Source: Consolidated Impacts Modeling System

The steel flow through the galvanizing step is given as follows:

$$Cold\_Galv_y = SumProdCur_{IS=2,y} * Galv\_Shr$$

(237)

where

$Cold\_Galv =$ Tonnes of cold-rolled steel from the galvanizing process; and

$Step\_Shr_{ISX=2} =$ Historical share of cold-rolled galvanized steel technology ISX=2, from AISI 2012 data.

The energy demand for the galvanizing step is calculated as follows:

$$Energy\_Use_{IS=2,IX=2,f,y} = \sum_{Proc=1}^{2} Cold\_Galv * Proc\_Shr_{Proc,IX=2} * Fuel\_Use_{Proc,f,IX=2} \quad (238)$$

Electrocleaning: ISX = 3

The electrocleaning step is a predecessor to the manufacture of specialized products. Steel that does not pass through the Galvanizing step is assumed to pass through electrocleaning, calculated as follows:

$$Cold\_Electro_y = SumProdCur_{IS=2,y} * (1 - Galv\_Shr) \quad (293)$$

where

$Cold\_Electro_y$ =   Tonnes of cold-rolled steel from the electrocleaning process.

Table 45. Electroclean allocation shares and process characteristics

	Process share	Natural_gas (million British thermal units per kilotonne)	Heavy fuel oil (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)
Electroclean preparation	100.0%	0	0	94	0
Anneal temper	92.8%	903	95	156	55
Tin plate	19.2%	0	0	571	0
Electric steel	2.7%	2,612	133	1,738	147

Source: Consolidated Impacts Modeling System

$$Energy\_Use_{IS=2,IX=3,f,y} =$$

$$Cold\_Electro_y * Fuel\_Use_{Prep,f,IX=3}$$

$$+ \sum_{Proc=1}^{3} Cold\_Electro * Proc\_Shr_{Proc,IX=3} * Fuel\_Use_{Proc,f,IX=3} \quad (239)$$

And the total energy demand for the Cold Rolling step is calculated as follows:

$$Tot\_Energy\_Use_{IS=2,f,y} = \sum_{IX=1}^{3} Energy\_Use_{IS=2,IX,f,y} \quad (240)$$

Continuous Casting: IS = 3

Continuous casting comprises three steps: reheating, refining, and form production, of which only one (reheating) requires a technology choice. The figure below depicts the material flows through this step.

Figure 20. Continuous casting technology model flow
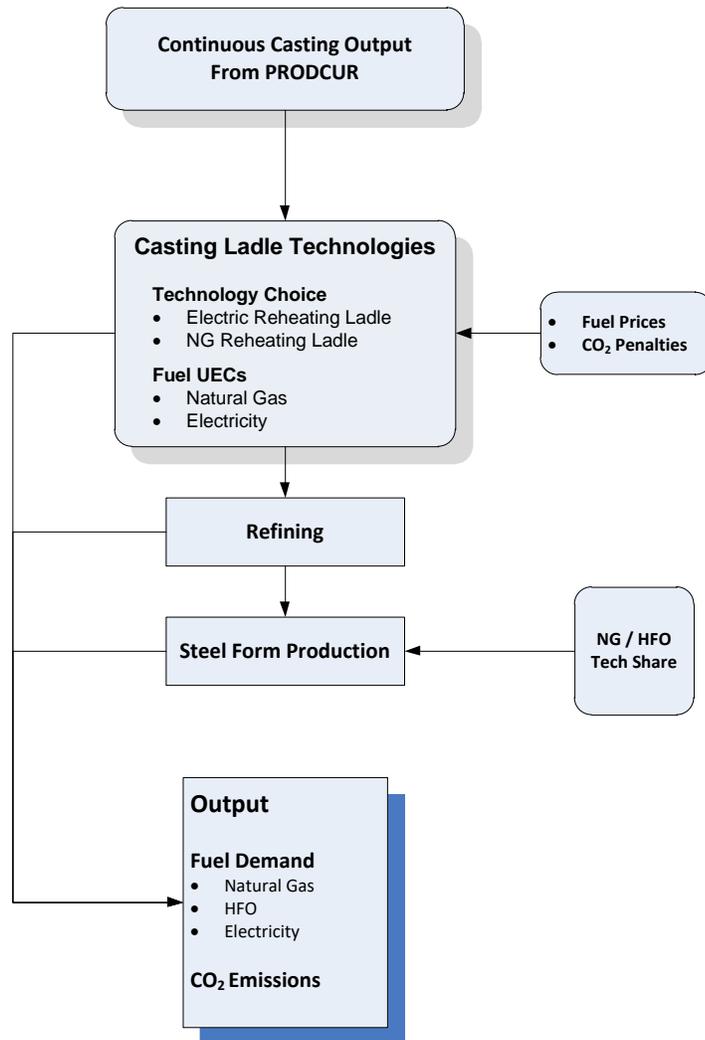
Source: U.S. Energy Information Administration

Regional PRODCUR estimates are first summed to provide a national total of cold-rolled steel production, $SumProdCur_{IS=3,y}$.

Table 46. Continuous casting ladle energy and technology characteristics

Technology	Technology share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)

Reheating   ISX = 1

Electric ladle reheating	99.9%	601	0	75	0
Natural gas ladle reheating	0.1%	455	660	0	35
Refining ISX = 2					
Ladle refining	100%	--	--	94	--

Source: U.S. Energy Information Administration

Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{IS=3,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc on (see page 104) chooses the technologies for the added capacity. Energy and technology characteristics are shown in Table 46.

Table 47. Continuous casting form energy and technology characteristics

Technology	Initial technology share (base year)	Final technology share (2030)	Natural gas (million British thermal units per kilotonne)	Heavy fuel oil (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tons per kilotonne)
Steel forms: natural gas	90.0%	80.0%	522	--	70	27
Steel forms: oil	10.0%	20.0%	--	522	70	40

Source: U.S. Energy Information Administration

The energy required for this step is calculated as follows:

$$Energy\_Use_{IS=3,f,IX=3} = \sum_{Tech} Tot\_Prod\_Tech_{IS=3,Tech} * F\_Share_f * Fuel\_Use_{f,IX=3} \qquad (241)$$

Total energy use for continuous casting is calculated as follows:

$$Tot\_Energy\_Use_{IS=3,f,y} =$$

$$\sum_{Tech=1}^{2} Tot\_Prod\_Tech_{IS=3,IX=1,Tech,y} * Fuel\_Use_{IS=3,IX=1,f,Tech}$$

$$+ SumProdCur_{IS=3,IX=2,y} * Fuel\_Use_{IS=3,IX=2,f}$$

$$+ \sum_{Tx=1}^{2} Tot\_Prod\_Tech_{IS=3,IX=3,Tx,y} * Fuel\_Use_{f,IX=3} * F\_Share_{f,y} \qquad (242)$$

Blast Furnace/Basic Oxygen Furnace: IS = 4

The Blast Furnace/Basic Oxygen Furnace (BF/BOF) produces raw steel that is passed to the Continuous Casting step above. The BF/BOF uses coal, natural gas, and electricity. Steam and oxygen are major non-energy inputs. Fuel use for energy inputs and electricity use for oxygen production are calculated in this step. Fuel use for process steam requirements is calculated in subroutine Steel_BSC, which is described starting on page 161. Figure 21 depicts the flows within this step.

Figure 21. Blast furnace technology model flow
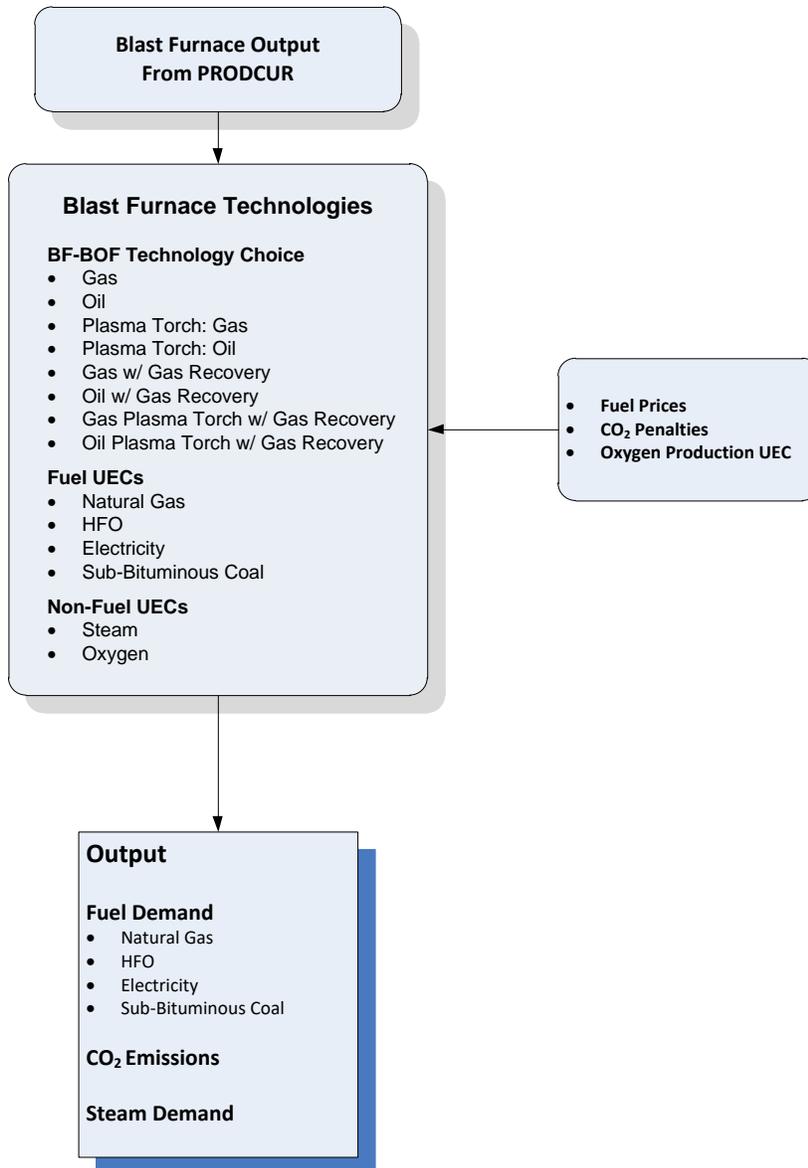
Source: U.S. Energy Information Administration

The physical output for this step is $SumProdCur_{IS=4,y}$ which is equal to the sum of $qBF/BOF_{r,y}$ (defined on page 139) summed across the four Census regions:

$$SumProdCur_{IS=4,y} = \sum_{r=1}^{4} prodcur_{IS=4,y} = \sum_{r=1}^{4} qBF/BOF_{r,y} \qquad (243)$$

Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{IS=4,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc on (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fuel use, steam, and oxygen consumption can be calculated.

Fuel consumption is calculated for each technology as follows:

$$Energy\_Use_{IS=4,f,Tech,y} = Tot\_Prod\_Tech_{IS=4,Tech,y} * Fuel\_Use_{IS=4,f,Tech} \qquad (244)$$

The steam demand for this step is calculated as follows:

$$Steam\_Dmd_{IS=4,Tech,y} = Tot\_Prod\_Tech_{IS=4,Tech,y} * Steam\_Use_{IS=4,Tech} \qquad (245)$$

Oxygen demand is calculated as follows:

$$Oxy\_Dmd_{IS=4,Tech} = Tot\_Prod\_Tech_{Tech,} * Oxy\_Use_{Tech} \qquad (246)$$

where

$Tot\_Prod\_Tech_{IS=4,Tech,y}$ =BF/BOF material output produced using technology $Tech$ in year y;

$Fuel\_Use_{IS=4,f,Tech}$ = Unit energy consumption of fuel f using technology $Tech$ in MMBtu/kT, which is specified in the input file ironstlx.xls and shown in Table 48;

$Steam\_Dmd_{IS=4,Tech,y}$ = Gigajoules of steam required for the BF/BOF processes $Tech$ in year y;

$Steam\_Use_{IS=4,Tech}$ = Steam use in the BF/BOF process for technology $Tech$ in GJ/kT, which is specified in the input file ironstlx.xls and shown in Table 49;

$Oxy\_Dmd_{IS=4,Tech}$ = Tonnes of oxygen required for the technology $Tech$; and

Oxy_Use_{Tech} = Oxygen use for technology $Tech$ in tonnes/kT, which is specified in the input file ironstlx.xls and shown in Table 49.

Total energy consumption for this step, excluding energy used in steam production, is calculated by summing across technologies for this step.

For fuels except electricity, the calculations are as follows:

$$Tot\_Energy\_Use_{IS=4,f \neq Elec,y} = \sum_{Tech=1}^{8} Energy\_Use_{IS=4,f,Tech,y} \qquad (247)$$

For electricity, which includes electricity used in the production of oxygen, the calculations are as follows:

$Tot\_Energy\_Use_{IS=4,f=Elec,y}$

$$= \sum_{Tech=1}^{8} \left[Energy\_Use_{IS=4,f=Elec,Tech,y} + \left(Oxy\_Dmd_{IS=4,Tech,y} * Oxy\_UEC_{f=Elec} \right) \right] \quad (\,248\,)$$

where

$Tot\_Energy\_Use_{IS=4,f,y}$ = BF/BOF energy use for fuel f and year y, excluding steam; and

$Oxy\_UEC_{f=Elec}$ =   MMBtu of electricity per tonne of oxygen produced, using cryogenic air compression and distillation. It is held constant at a value of 0.162318 MMBtu/tonne.

Energy required to produce steam is not included in this step; fuel use for process steam requirements are calculated in subroutine Steel_BSC, which is described starting on page 161.

Table 48. Blast furnace/basic oxygen furnace energy consumption characteristics

Blast furnace technology	Basic oxygen furnace technology	Technology share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	Heavy fuel oil (HFO) (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Coal (million British thermal units per kilotonne)
Plasma torch	Natural gas	86.6%	350,518	1,046		521	587
Coke	Natural gas	8.0%	350,518	-3,207		528	744
Plasma torch	Oil	3.0%	352,739	-2,891	3,936	506	587
Coke	Oil	2.0%	352,739	-3,663	454	542	744
Coke	Natural gas with recovery	0.1%	350,576	-3,683		528	744
Coke	Oil with recovery	0.1%	352,797	-4,139	454	542	744
Plasma	Natural gas with recovery	0.1%	350,576	570		521	587
Plasma	Oil with recovery	0.1%	352,797	-3,367	3,936	506	587

Source: Consolidated Impacts Modeling System

Note: The energy in blast furnace gas (BFG) and coke oven gas (COG), which are produced in the steelmaking process, is deducted from natural gas consumption. A negative value of natural gas consumption means the energy in BFG and COG exceeds natural gas energy consumption.

Table 49. Blast furnace/basic oxygen furnace non-energy consumption characteristics

Blast furnace technology	Basic oxygen furnace technology	Technology share (base year)	Steam (gigajoules per kilotonne)	Oxygen (tonnes per kilotonne)	Carbon dioxide emissions (tonnes per kilotonne)
Plasma torch	Natural gas	86.6%	3,828	180	1,305
Coke	Natural gas	8.0%	3,848	170	1,416
Plasma torch	Oil	3.0%	3,828	170	1,401
Coke	Oil	2.0%	3,848	180	1,427
Coke	Natural gas with recovery	0.1%	3,848	180	1,391
Coke	Oil with recovery	0.1%	3,848	170	1,402
Plasma	Natural gas with recovery	0.1%	3,828	180	1,280
Plasma	Oil with recovery	0.1%	3,828	170	1,376

Source: Consolidated Impacts Modeling System

Electric Arc Furnace: IS = 5

Like the BF/BOF step above, the Electric Arc Furnace (EAF) produces raw steel that is passed to the Continuous Casting step. The EAF uses natural gas and electricity. Steam and oxygen are major non-energy inputs. Fuel use for energy inputs and electricity use for oxygen production are calculated in this step. Fuel use for process steam requirements is calculated in subroutine Steel_BSC, which is described starting on page 161. Figure 22 depicts the flows within this step.

Figure 22. Electric arc furnace technology model flow
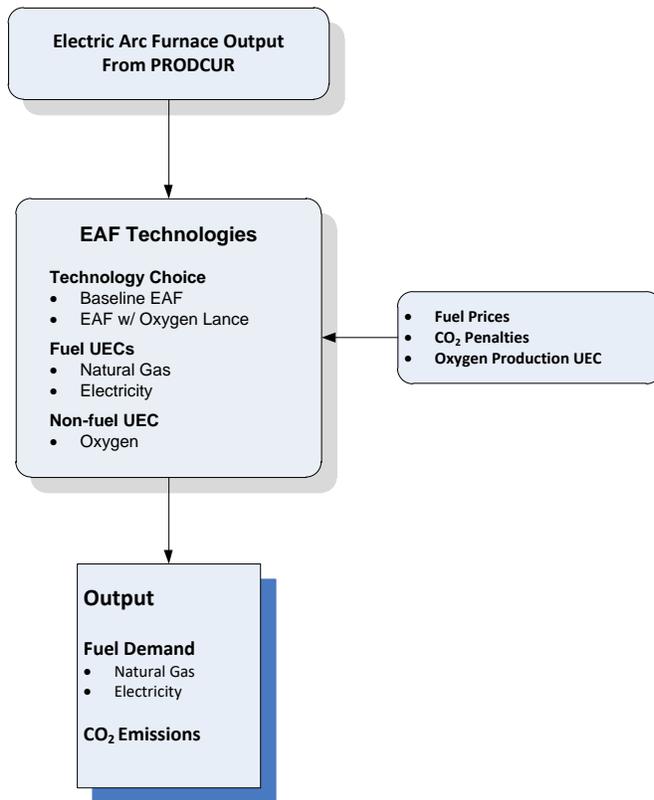
Source: U.S. Energy Information Administration

The physical output for this step is $SumProdCur_{IS=5,y}$ is calculated in Subroutine IS_PRODCUR_Breakout (see page 135) in which is equal to the $qEAF_{r,y}$ summed across regions.

Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{IS=5,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc on (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fuel use, steam, and oxygen consumption can be calculated by technology. Energy and technology characteristics are shown in Table 50.

Fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step as follows:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{IS=5,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{IS=5,Tech,y}$ is shown on page 150.
- o The calculation for quantity of oxygen demanded technology, and year, $\_Dmd_{IS=5,Tech}$, is shown on page 150.

Once fuel consumption is calculated by technology, total energy use by fuel can be calculated as follows:

o The calculation for total energy use by fuels other than electricity, $Tot\_Energy\_Use_{IS=5,f \neq Elec,y}$, is shown on page 150.

o The calculation for total electricity use, which includes electricity used in oxygen production, $Tot\_Energy\_Use_{IS=5,f=Elec,y}$ is shown on page 150.

Table 50. Electric arc furnace (EAF) energy and technology characteristics

Technology	Technology share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Carbon dioxide emissions (tonnes per kilotonne)	Oxygen (tonnes per kilotonne)
EAF, water cooled, preheated scrap	30%	74,437	332	1,288	17	0
EAF, water cooled, oxygen lance	70%	68,726	332	1,215	17	5

Source: Consolidated Impacts Modeling System

Direct Reduced Iron: IS = 6

Direct Reduced Iron (DRI) is used to feed both BF/BOF and EAF processes. DRI currently represents a very small component of iron production, but shows potential for greater penetration in the future. The EAF uses natural gas and electricity. Steam and oxygen are major non-energy inputs. Fuel use for energy inputs and electricity use for oxygen production are calculated in this step. Fuel use for process steam requirements is calculated in subroutine Steel_BSC, which is described starting on page 161. Figure 22 depicts the flows within this step. The total production of DRI is currently exogenously specified, and PRODFLOW matrix elements are adjusted to ensure that the PRODCUR results match the specified production. The process flows for this step are shown in Figure 23.

Figure 23. Direct reduced iron model flow
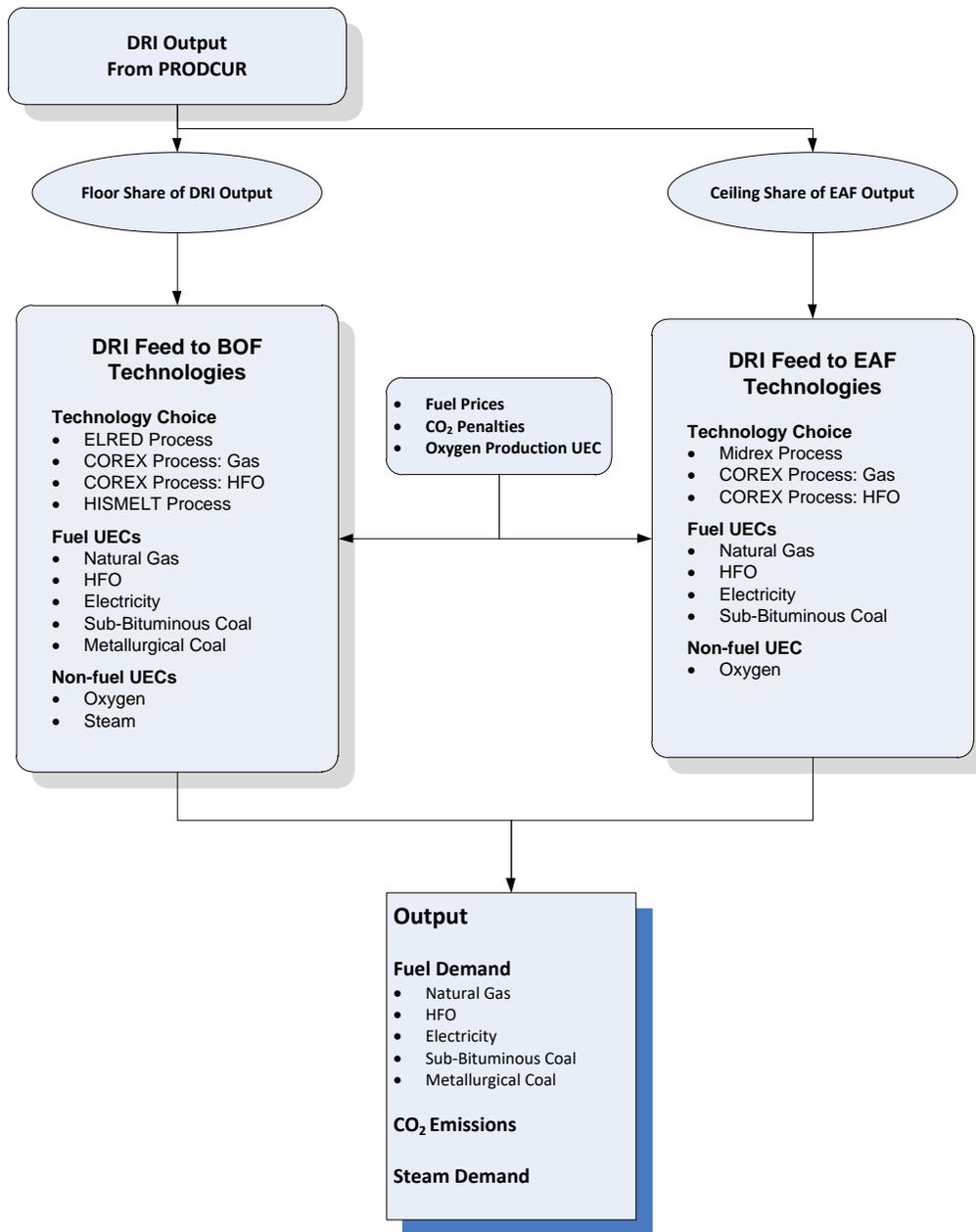
Source: U.S. Energy Information Administration

The physical output for this step is $SumProdCur_{IS=5,y}$ is calculated in Subroutine IS_PRODCUR_Breakout (see page 135) in which is equal to the $qEAF_{r,y}$ summed across regions.

The tonnage of material flowing through this step is calculated using equation 290 on page 141 with industrial technology step IS=6.

The technology choices for producing DRI depend on whether it is to be used as a feed to the BOF or EAF step. The model constrains its flow of DRI as follows:

- A minimum percentage of DRI production must feed BOF systems.
- DRI can represent a maximum percentage of EAF production.
- All DRI remaining after meeting the above two conditions feeds BOF systems, subject to the constraint that it cannot exceed the total output of BOF.

Specifically, the flow of DRI to BOF is calculated as follows (indexes for the year are implicit):

$$DRI_{BOF_y} = qDRI_y * BOF\_Share$$

$$+MAX\big[0, qDRI_y * (1 - BOF\_Share) - \big(qEAF_y * EAF\_Share\big)\big] \quad (\,249\,)$$

where

DRI_Tot	=	Total production of DRI to be allocated;
BOF_Share	=	Minimum Share of DRI production to go to BOF;
EAF_Prod	=	Total output of the EAF process; and
EAF_Share	=	Maximum share of EAF production that can be DRI.

And the flow of DRI to EAF is then calculated as follows:

$$DRI\_EAF = qDRI_y - DRI\_BOF_y \qquad\qquad (\,250\,)$$

where

DRI_EAF_y =		Total production of DRI for EAF systems; and
DRI_BOF_y =		Total production of DRI for BOF systems.

DRI_BOF and DRI_EAF are used as the process flow estimates, and input into the corresponding technology choice subroutine using the technology shares and characteristics are shown in Table 51 and Table 52.

Table 51. Direct reduced iron energy and technology characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	HFO (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Coal (million British thermal units per kilotonne)	Metallurgical coal (million British thermal units per kilotonne)
DRI to BOF							
ELRED combined cycle (natural gas)	0.1%	427,736	1,540	0	-561	693	0
COREX process (natural gas)	79.9%	301,808	2,115	0	1,126	0	12,896
COREX process (oil)	0.1%	303,559	0	2,189	1,158	0	12,896
Hismelt process (natural gas)	19.9%	294,546	199	0	294	809	0
DRI to EAF							

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	HFO (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Coal (million British thermal units per kilotonne)	Metallurgical coal (million British thermal units per kilotonne)
Midrex process (natural gas)	94.9%	272,302	458	0	1,522	587	437
COREX process (natural gas)	5.0%	274,079	0	455	1,522	587	437
COREX process (oil)	0.1%	426,057	10,051	0	2,065	0	291

Source: Consolidated Impacts Modeling System

Table 52. Direct reduced iron non-fuel characteristics

Technology	Tech share (base year)	Steam (gigjoules per kilotonne)	Oxygen (tonnes per kilotonne)	CO2 emissions (tonnes per kilotonne)
DRI to BOF				
ELRED combined cycle (natural gas)	0.1%	131	0	1,558
COREX process (natural gas)	79.9%	131	80	94
COREX process (oil)	0.1%	131	80	134
Hismelt process (natural gas)	19.9%	131	25	1,733
DRI to EAF				
Midrex process (natural gas)	94.9%	0	1,274	0
COREX process (natural gas)	5.0%	0	1,284	0
COREX process (oil)	0.1%	0	528	0

Source: Consolidated Impacts Modeling System

Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{IS=5,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc on (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fuel use, steam, and oxygen consumption can be calculated by technology. Energy and technology characteristics are shown in Table 50.

Fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step as follows:

- The calculation for energy use by fuel, technology, and year, $Energy\_Use_{IS=5,f,Tech,y}$, is shown on page 150.
- The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{IS=5,Tech,y}$ is shown on page 150.
- The calculation for quantity of oxygen demanded by fuel, technology, and year, $\_Dmd_{IS=5,Tech}$, is shown on page 150.

Once fuel consumption is calculated by technology, total energy use by fuel can be calculated:

- The calculation for total energy use by fuels other than electricity, $Tot\_Energy\_Use_{IS=5,f\neq Elec,y}$, is shown on page 150.
- The calculation for total electricity use, which includes electricity used in oxygen production, $Tot\_Energy\_Use_{IS=5,f=Elec,y}$ is shown on page 150.

Energy required to produce steam is not included in this step; fuel use for process steam requirements are calculated in subroutine Steel_BSC, which is described starting on page 161.

Coke Production: IS = 7

The physical output for this step is $SumProdCur_{IS=5,y}$ is calculated in Subroutine IS_PRODCUR_Breakout (see page 135) in which is equal to the $qEAF_{r,y}$ summed across regions. The amount of coke actually required to be produced is somewhat different, as it must account for net coke imports and the offsetting impact of introducing DRI (which requires no coke) to the BOF system. Like the cold rolling step (IS=2), Coke production requires no technology choice; it is simply an accounting of the requirement for domestically produced coke, and the energy required to manufacture it.

First, the net coke requirement must be calculated by subtracting the avoided production stemming from the introduction of DRI, as follows:

$$Net\_Coke_y = qCoke_y - DRI\_BOF * CokeFact \tag{293}$$

where

Net_Coke	=	Net coke required to produce the estimated production of BF/BOF steel;
DRI_BOF	=	Amount of DRI introduced to the BF/BOF system, in kilotonnes; and
$CokeFact$	=	0.39, constant conversion factor to estimate the tonnes of coke production avoided.

The amount of BF/BOF steel produced is then adjusted to estimate non-DRI production. This result is used to estimate and constrain subsequent adjustments from Net Coke Imports:

$$NON\_DRI\_BOF_y = qBF\_BOF_y - DRI\_BOF_y \tag{251}$$

where

qBF_BOF_y=   Total production of BF/BOF steel (IS = 4); and

NON_DRI_BOF = Total non-DRI production of BF/BOF steel.

Net imports of coke (NI) can increase or decrease the amount of coke required to be domestically produced. NI is estimated through regression, based on historical data, and depends on its lagged value and changes in the production of BF/BOF steel. The estimation of NI is:

$$NI_y = NI_{y-1} - 0.3872 * \left(NI_{y-1} - NI_{y-2}\right)$$

$$+0.1239 * \left(NON\_DRI\_BOF_y - NON\_DRI\_BOF_{y-1}\right) \quad (\,252\,)$$

where

NI_y =   Total net imports of coke in year y.

As the above NI_y estimation equation is unbounded, it is necessary to impose an additional constraint so that the forecast does not produce an unrealistic estimate of imports or exports. Accordingly, the function is constrained so that when it evaluates as a negative (that is, exports), it does not exceed a specified percentage of the Net Coke Requirement for making BOF steel. This requirement is currently set at 10%, which represents the maximum historical share of negative Net Imports (exports). This percentage is intended to acknowledge the decreasing reliance on BF/BOF production in the United States, and the expected limitation on the availability of coke for export. The constraint is imposed as follows:

$$C\_NI_y = MAX\left[NI_y, (-Net\_Coke_y * Max\_Pct)\right] \qquad (\,253\,)$$

where

C_NI_y =   Constrained net imports of coke in year y; and

Max_Pct =   Maximum percentage of domestically produced coke available for export.

Accounting for the coke production avoided through the use of DRI and the adjustment to production from imports or exports, the total coke production requirement is expressed as follows:

$$Coke\_Prod_y = Net\_Coke_y - C\_NI_y \qquad (\,254\,)$$

where

$Coke\_Prod_y$ =   Total coke production in kilotonnes in year y.

The energy and other inputs required to produce a tonne of coke is obtained from the RTI report[51] and summarized in Table 53.

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[51] Figure F-1, *Industrial Technology and Data Analysis Supporting the NEMS Industrial Model*, FOCIS Associates, Inc., October 2005.

Table 53. Coke production energy consumption characteristics

Natural gas	Heavy fuel oil	Metallurgical coal	Blast furnace gas	Coke oven gas (input)	Coke oven gas (output)	Steam (gigajoules per kilotonne)	Electricity
15.4	11.0	42,659	115.7	3,401	-9,579	1,590	121.3

Source: Consolidated Impacts Modeling System

Note: Units in million British thermal units per kilotonne, except for steam.

The energy and material requirement for the coke production step is then given by the following:

$$Tot\_Energy\_Use_{IS=7,f,y} = Coke\_Prod_y * Fuel\_Use_{f,y} \qquad (255)$$

This steam demand for this step is given as follows:

$$Steam\_Dmd_{IS=7,y} = Coke\_Prod_y * Steam\_Use_y \qquad (256)$$

Subroutine Steel_BSC: Energy for Steam Production

Process steam is used in the production of BF/BOF steel, DRI, and coke. This steam is produced by either conventional boilers or CHP systems. Steam produced by CHP is also used to generate electricity, which is used to offset electricity demand in other process steps.

Total steam demand is first calculated as follows:

$$Tot\_Steam_y = BTU\_Conv * \sum_{IS \in 4,6,7} Steam\_Dmd_{IS,y} \qquad (257)$$

where

Tot_Steam = Total process steam required by all steps (MMBTu);

$Steam\_Dmd_{IS,y}$ is calculated on 150; and

$BTU\_Conv = \dfrac{1}{1.054615}$ unit conversion constant that converts gigajoules to MMBTu.

Steam production is then allocated between conventional and CHP systems as follows:

$$Boil\_Steam_y = Tot\_Steam_y * Boil\_Share \qquad (258)$$

$$CHP\_Steam_y = Tot\_Steam_y * (1 - Boil\_Share) \qquad (259)$$

where

$Boil\_Steam$ = Total steam produced by conventional boilers (gigajoules);

CHP_Steam = Total steam produced by CHP systems (gigajoules); and

$Boil\_Share$ = Fraction of total steam produced by boilers, currently held constant at 5%.

The technologies associated with boiler and CHP systems are described in the following table. The fuel shares have been calibrated to comport with MECS 2014 estimates. The allocation of steam production to each of the technologies is exogenously specified in the initial and final years of the forecast, and the shares for the intervening years are calculated by linear interpolation between those points.

Table 54. Steam and CHP production shares and energy intensities

	Technology Share		Natural Gas MMBtu/GJ	HFO MMBtu/GJ	Electricity MMBtu/GJ	Coal MMBtu/GJ	CO2 Emissions T/GJ Steam
	2015	2050					
Boiler Technologies (IX = 1) of which:	**20%**	**26%**					
NG Boiler	27%	35%	1.19	0.00	0.00	0.00	0.062
Coal Boiler	70%	15%	0.00	0.00	0.00	1.16	0.113
HFO Boiler	1%	1%	0.00	1.16	0.00	0.00	0.089
Coal Boiler, CCS	1%	15%	0.00	0.00	0.05	1.48	0.012
NG Boiler, CCS	1%	34%	1.31	0.00	0.04	0.00	0.001
CHP Technologies (IX = 2) of which:	**80%**	**74%**					
NG Turbine	28%	35%	1.33	0.00	-0.105	0.00	0.070
Coal Turbine	71%	30%	0.00		-0.105	1.30	0.126
HFO Turbine	1%	1%	0.00	1.33	-0.105	0.00	0.102
NG CHP, BPST CCS	0%	34%	1.47	0.00	-0.070	0.00	0.008

Source: Consolidated Impacts Modeling System

The energy required to produce steam is calculated as follows:

$$Boiler\_Energy\_Use_{f,y}$$

$$= \sum_{Tech} Boil\_Steam_{Tech,y} * Tech\_Shr_{Tech,y} * Fuel\_Use_{Tech,f} \qquad (260)$$

$$CHP\_Energy\_Use_{f,y} = \sum_{Tech} CHP\_Steam_{Tech,y} * Tech\_Shr_{Tech,y} * Fuel\_Use_{Tech,f} \qquad (261)$$

where

$Tech\_Shr_{Tech,y}$ = Exogenously specified share of boiler/CHP technology Tech used to produce steam; and

$Fuel\_Use_{Tech,f}$ = Unit energy consumption fuel f for steam production, in MMBtu/GJ of steam produced as shown in Table 54.

$Steam\_Fuel\_Dmd_{f,y}$ = $Boiler\_Energy\_Use_{f,y} + CHP\_Energy\_Use_{f,y}$ (262)

In the case of CHP systems, the negative figure calculated for electricity represents the energy content of generated electricity. For reporting purposes, this is converted to kWh of electricity generation as follows:

$$Elec\_Gen_y = \frac{CHP\_Energy\_Use_{Elec,y}}{(3412\ Btu/kWh)} * 10^6 \qquad\qquad (\ 263\ )$$

Subroutine TECH_STEP:Industry Energy Demand

Total energy demand by fuel is computed directly in subroutine TECH_STEP. Energy consumption is the sum of fuel demands. First, fuel demand for each process step is summed as follows:

$$NonSteam\_Energy\_Use_{f,y} = BTU\_Conv * \sum_{IS=1}^{7} Energy\_Use_{IS,f,y} \qquad\qquad (\ 264\ )$$

Adding boiler and CHP fuel consumption yields total energy consumption, as follows:

$$Total\_Q_{f,y}$$

$$= Boiler\_Energy\_Use_{f,y} + CHP\_Energy\_Use_{f,y} + Non\_Steam\_Energy\_Use_{f,y} \qquad (\ 265\ )$$

where

$Total\_Q_{f,y}$ = Total demand for energy, by fuel and year

BTU_Conv = Conversion factor to convert gigajoules to trillion Btu;

$Boiler\_Energy\_Use_{f,y}$ and $CHP\_Energy\_Use_{f,y}$ are defined above;

 and

$Energy\_Use_{IS,f,y}$ = Total demand for energy, by fuel f, within each process step in gigajoules.

Unique Iron and Steel Model calculations

Creating a Dynamic PRODFLOW Matrix

With a dynamic PRODFLOW, the mass of material going through each process step changes based on exogenous factors. The highlighted cells in the above table are coefficients that are subject to change, either by linking to exogenous factors such as fuel price, or by direct adjustment to reflect the future introduction of new capacity. The dynamic elements are as follows:

1. Share of cold-rolled steel, expressed as a percentage of hot-rolled production
2. Share of EAF versus BF/BOF (currently approximately 60% versus 40%, but with regional differences, and subject to change)
3. DRI inputs to EAF—currently zero, but with new capacity expected in the next few years, driven by low gas prices
4. Coke inputs into the BF/BOF stage

Cold-rolled steel share

Cold-rolled steel percentage is inferred from other MAM output: the value of output of fabricated metals, machinery, and transportation equipment are tentatively considered proxies for the demand for cold-rolled steel, and construction is considered a proxy for hot-rolled steel demand. A proxy value is first calculated as follows:

$Cold\_Proxy_{r,y}$

$$= \left[\frac{Outind_{FabMet,r,y} + Outind_{Mach,r,y} + Outind_{TranEq,r,y}}{Outind_{FabMet,r,y} + Outind_{Mach,r,y} + Outind_{TranEq,r,y} + Outind_{Const,r\,y}} \right] \quad (\,266\,)$$

where

$Outind_{xx,r,y}$ = Value of shipments, obtained from MAM, for industry xx, region r, and year y. Industries in xx include Fabricated Metals (FabMet), Machinery (Mach), Transportation equipment (TranEq) and construction (Const).

This value is then indexed to 2002, as follows:

$$Cold\_Index_{r,y} = \left[\frac{Cold\_Proxy_{r,y}}{Cold\_Proxy_{r,2002}} \right] \quad (\,267\,)$$

Regional production shares of cold-rolled steel are calculated by applying the index to the 2002 value of 39%. The result of this, using sample (AEO2013) data is as follows, showing an approximate ten to twenty percent increase in cold-rolled steel demand over the course of the forecast. This will have an impact on the energy required to fabricate steel products.

Share of EAF vs. BOF

The EAF/BOF split is currently initialized using regional elements of the PRODFLOW, adjusted using fuel price changes, and then renormalized so that their sum is equivalent to the base-year sum of coefficients.

More specifically, all of the output from the EAF and BOF steps is assumed to flow into the Continuous Casting step. According to the coefficients in the input/output matrix above, one tonne of casting output (in Region 1) would require 0.754 tonnes of EAF production and 0.310 tonnes of BOF production—a total of 1.064 tonnes of input for this region.

There are significant regional differences in these elements: Regions 2 and 3 each require a total of 1.113 tonnes of material input to the casting step, and Region 4 apparently suffers no waste, requiring 1.0 tonnes of EAF production (without any BOF) for each tonne produced in casting.

To adjust the PRODFLOW elements, the relative shares of EAF and BOF technologies are calculated, based on their initial shares and changes in the prices of their primary fuels: electricity for EAF and natural Gas for BOF, given as follows:

$$PRODFLOW_{y,Tech} = \left[\frac{P_{f,y,Tech}^{\gamma_f} * \theta_{Tech}}{\sum_f P_{f,y,Tech}^{\gamma_f} * \theta_{Tech}}\right] * \left(\sum_{Tech} PRODFLOW_{BaseYear,Tech}\right) \quad\quad (268)$$

where

$P_{f,y,Tech}$ = Fuel f price in year y, relative to the base year (2014) price;

γ_f = Fuel price sensitivity parameter (initially set to -2.0);

θ_{Tech} = Calibration coefficients used to reproduce base year PRODFLOW elements; and

$PRODFLOW_{y,Tech}$ = I/O matrix elements for EAF and BOF technologies.

As an example, for Region 1, the above function would shift production between EAF and BOF as follows:

This relationship is consistent with the expectation of a declining reliance on BOF over the course of the forecast.

DRI inputs to EAF

Beginning with this revised model, direct reduced iron (DRI) is included as a component of the I/O (that is, PRODFLOW) matrix. In contrast to other elements of the production process, DRI production is exogenously specified and flows into either BF or EAF production output. The coefficients dictating the flows of DRI to the subsequent production steps are calculated based on projected production/capacity expansion in each region, and then converted into a share of regional production for each of the steelmaking processes. The exogenous estimate of DRI production by region is as follows, based on review of available literature regarding industrial production plans:

Table 55. DRI production by region

Million tonnes/year	Region 1	Region 2	Region 3	Region 4
2015	0	0.20	1.80	0
2022	0	0.50	4.50	0

Source: Consolidated Impacts Modeling System

The following issues should be noted:

- The PRODFLOW matrix is intended to calculate the demand for output from a subsidiary step, and this approach backs into the coefficients, forcing the model to generate a pre-determined demand.

- Since DRI may be used in both EAFs and BFs, there should be a non-zero coefficients for DRI in the BF-BOF column of the **A** matrix.

- To accommodate these concerns, it was decided to constrain DRI inputs to EAF to a user-specified ceiling, and to specify a minimum floor for DRI inputs to BF's.

- After calculating the tonnage of DRI devoted to each subsequent process, the figures are converted to represent the fraction of BF or EAF output. These converted figures are the PRODFLOW factors that populate the I/O matrix.

- A detailed description of how DRI is allocated between BF and EAF is provided below, in the discussion of the model's material flows.

Coke inputs into the BF/BOF stage

The PRODFLOW elements associated with Coke production were recalibrated to ensure that the overall (national) impact would result in a production ratio more in line with the expected range of 0.35 to 0.40 tonnes of Coke per tonne of BOF steel and benchmarked to provide results that comport with USGS estimates of Blast Furnace Steel production in 2014.

Originally, these PRODFLOW elements were stipulated, falling linearly over a set time frame to a minimum value. The current model approach is to link the Coke element to the changes in the BOF PRODFLOW element (which essentially specifies the share of steel production that comes from BOF's).

$$Coke\_Fact_{r,y} = Coke\_Fact_{r,y-1} * \left(1.0 + Coke\_Calib * \left[\left(\frac{BOF\_Fact_{r,y}}{BOF\_Fact_{r,y-1}} \right) - 1.0 \right] \right) \qquad (\,269\,)$$

where

$Coke\_Fact_{r,y}$ = PRODFLOW element for coke production, by region r, in year y;

$Coke\_Calib$ = Calibration constant, 0.60, that governs the sensitivity of changes in coke production to changes in Blast Furnace steel production; and

$BOF\_Fact_{r,y-1}$ = PRODFLOW element for BOF steel production.

Using Dynamic PHDRAT to Generate PRODX

To convert dollar amounts to physical units for industries other than steel, a value is calculated to represent the baseline volume of production, using the value of output from MAM and the most recent Commodity Flow Survey (in this case, 2007). The resulting value per tonne of steel is considered fixed for the forecast. This static value (PHDRAT) is subsequently used to convert MAM projections of steel output from dollars to tonnes.

In contrast to the legacy approach, the revised PHDRAT for iron and steel is dynamic, based on the share of steel that is cold-rolled. Cold-rolled steel is processed more than hot-rolled steel and is therefore presumably more expensive. The unit price ($/tonne) of steel represents a weighted average price of the two forms of steel, and unit price of cold-rolled steel represents a premium over that of hot-rolled steel, owing to additional processing. If the mix of hot and cold-rolled steel changes, the weighed unit price will change, which implies the static PHDRAT assumption should change as well. First a base price is defined as follows:

$$BasePrice_r = \frac{\frac{PRODVX_{r,Base}}{PRODX_{r,Base}}}{(1 + \alpha_{r,Base}\beta)} \qquad (270)$$

$$NewPrice_{r,y} = BasePrice_r\,(1 + \alpha_{r,y}\beta) \qquad (271)$$

$$PRODX_{r,y} = \frac{PRODVX_{r,y}}{NewPrice_{r,y}} \qquad (272)$$

$PHDRAT_{r,y}$ is similar to $PHDRAT$ on page 44, but is now dynamic, as follows:

$$PHDRAT_{r,y} = \frac{PRODX_{r,y}}{PRODVX_{r,y}} \qquad (273)$$

where

$\alpha_{r,y}$ is the fraction of steel shipments represented by cold-rolled steel for region r in a given year y and is defined below; and

β is the cold-rolled price premium, which is a constant.

To calculate $\alpha_{r,y}$, for years after the base year, an index was created using MAM estimates of Metal-Based Durables (MBD) and Construction output as proxies for cold- and hot-rolled steel demand, respectively. This index, combined with the observation that cold-rolled steel represented 39% of the

shipments in 2002, was used to generate a sample forecast of the cold-rolled steel share, $\propto_{r,y}$, as follows:

$$\propto_{r,y}=\propto_{r,Base}*\left[\frac{\sum_{N=1}^{3}MAM\_Proxy_{N,r,y}\big/\sum_{N=1}^{4}MAM\_Proxy_{N,r,y}}{\sum_{N=1}^{3}MAM\_Proxy_{N,r,Base}\big/\sum_{N=1}^{4}MAM\_Proxy_{N,r,Base}}\right] \qquad (\,274\,)$$

where

> $MAM\_Proxy_{N,r,y}$=The value of shipments in the associated industry, N, from the MAM for region r and year y;
>
> $N \in \{1-4\}$ MAM industries: 1 = fabricated metals; 2 = machinery; 3 = transportation equipment; 4 = construction;
>
> $Base$ =   The base year relative to which changes are measured, corresponding to the year for which hot-rolled/cold-rolled shipment data are available (2002); and
>
> $\alpha_{r,y}$ =   Regional share of steel production that is cold-rolled for region r and year y.

The result of this is that the weighted steel price, based on a gradually increasing share of cold-rolled steel, trends upward over the forecast period. The volume of steel output under this approach is somewhat lower than originally forecast with the static unit value. The regional changes in the share of hot-rolled vs. cold-rolled steel calculated in this section will also have an impact on the input/output coefficient matrices (PRODFLOW).

The following chart shows the relative impact on regional steel production:

Figure 24. Impact of dynamic versus static PHDRAT
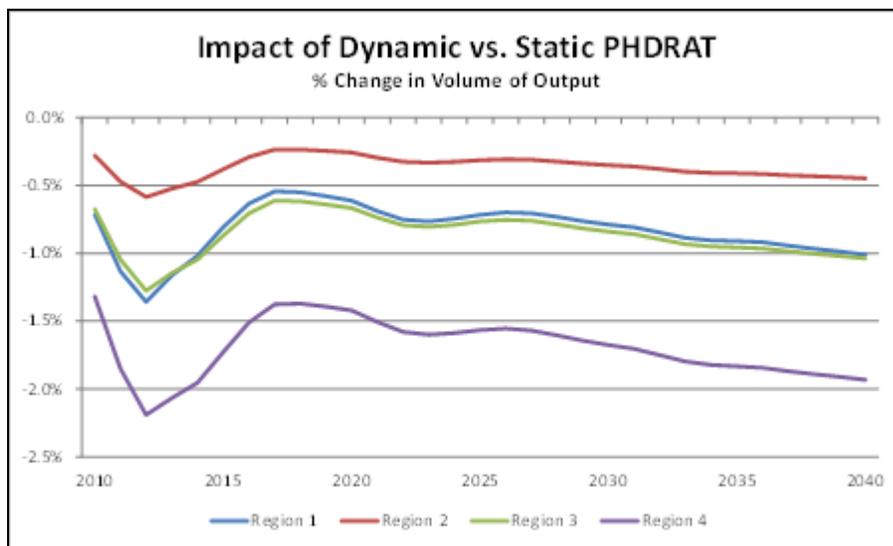
PULP AND PAPER INDUSTRY

Pulp and Paper Model Flow

The Pulp and Paper (P&P) model, like other energy-intensive industry models, is based on estimated flows of material across several process steps to ultimately meet final demand projections generated by the Macroeconomic Activity Model (MAM). The basic flows are depicted in Figure 25:

Figure 25. Detailed pulp and paper model flow
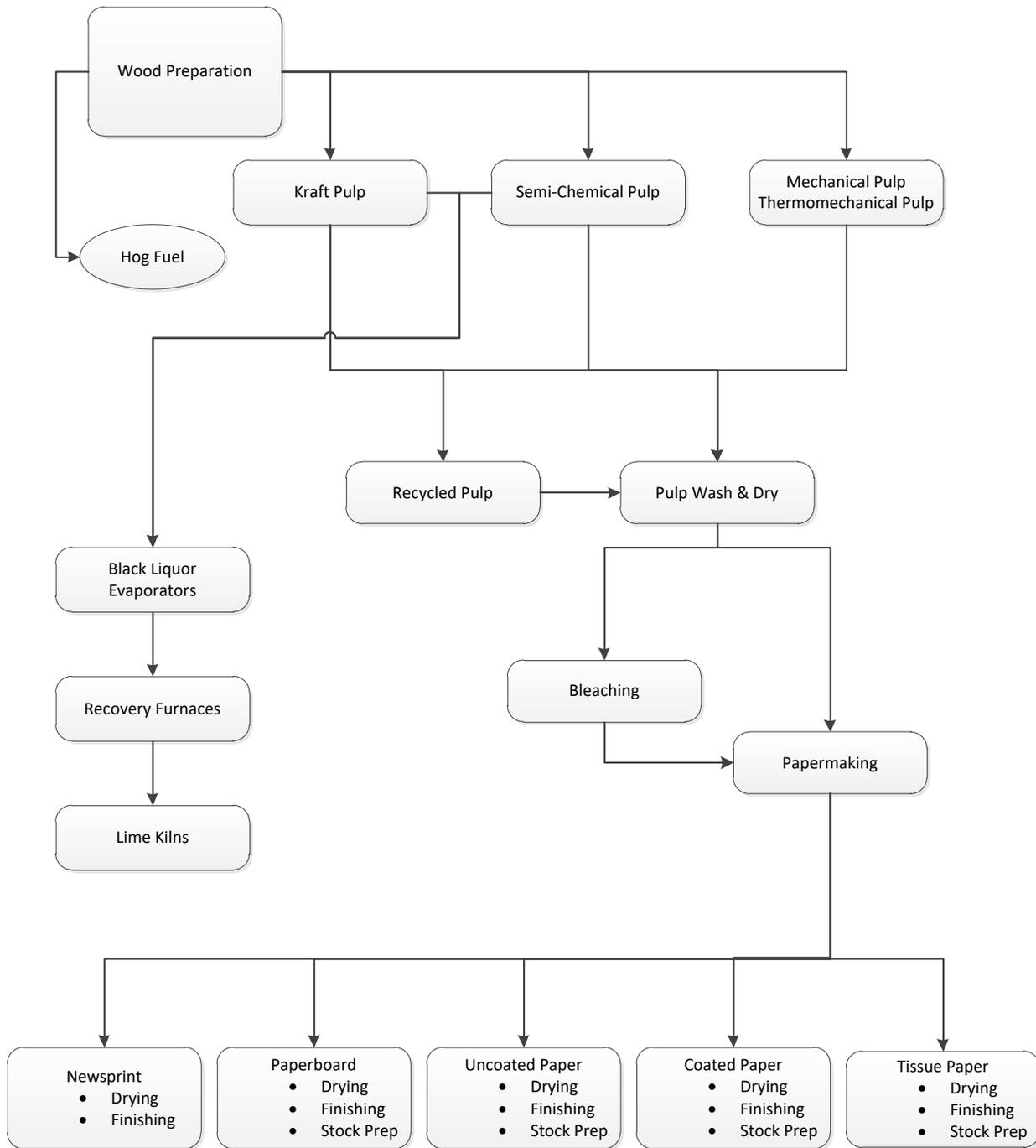
Source: U.S. Energy Information Administration

Process Flow Determination

The P&P model separately addresses material flows through each of a series of component steps. These steps represent the intermediate (and occasionally competing) processes that are required to produce

the volume of paper output projected by the MAM. The subroutine *PP_ProdcurBreakout* calculates these material flows, and is very similar to IS_PRODCUR Breakout, which is described on page 135.

Subroutine PP_Proxy

For two of the PRODCUR process steps, Papermaking (is = 1) and Mechanical Pulping (is = 4), it is necessary to subdivide the flows to feed different subprocesses. Papermaking is divided into five product types, and mechanical pulping is divided into two separate processes by Subroutine PP_PROXY, as described on page 197.

Subroutine PP_ProdcurBreakout

The PRODCUR calculation produces estimates of material flow for seven process steps and four census regions. The P&P model requires the flows to be aggregated into national totals and then broken out into sub-steps that will be used as inputs to the technology choice models.

Table 56 presents the individual process steps in the P&P model, the number of subprocesses within each step, and the subprocess step indexes used in the model code. Each of these model steps will be discussed separately, following the determination of productive capacity and its allocation among competing technologies.

Table 56. Pulp and paper model process steps and subprocess step indexes

P&P Model Step	Associated PRODCUR elements	Number of processes	P&P model process (ISX)	PRODCUR step index (IS)
Wood prep	Wood prep	1	1	7
Kraft pulp	Kraft pulp	1	2	6
Semi-chemical pulp	Semi-chemical pulp	1	3	5
Mechanical pulp	Mechanical pulp	1	4	4
Thermomechanical pulp		1	5	
Recycled pulp	Papermaking, virgin pulp	1	6	$1, 4-6$
Pulp wash and dry	Virgin and recycled pulp	2	7, 8	$3-6$
Bleaching	Bleaching	1	9	2
Newsprint		2	10, 11	
Paperboard		3	$12-14$	
Coated paper	Papermaking	3	$15-17$	1
Uncoated paper		3	$18-20$	
Tissue paper		3	$21-23$	
Evaporators		1	24	
Lime kilns	Black liquor	1	25	N/A
Recovery Furnaces		1	26	

Source: Consolidated Impacts Modeling System

Physical output is determined by subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Physical output is broken into 26 products. Unlike steel, there is not a one-to-one correspondence between PRODCUR and steps in the paper model. Physical flows are as follows:

$$qWoodPrep_{r,y} = prodcur_{ISX=1,r,y} \qquad (275)$$

$$qKraftPulp_{r,y} = prodcur_{ISX=2,r,y} \qquad (276)$$

$$qSemiChemPulp_{r,y} = prodcur_{ISX=3,r,y} \qquad (277)$$

$$qMechPulp_{r,y} = prodcur_{ISX=4,r,y}$$

$$= Mech\_Share_y * qTotalMechPulp_{r,y} \qquad (278)$$

$$qThermoMechPulp_{r,y} = prodcur_{ISX=5,r,y}$$

$$= \left(1 - Mech\_Share_y\right) * qTotalMechPulp_{r,y} \qquad (279)$$

$$qRecycledPulp_{r,y} = prodcur_{ISX=6,r,y}$$

$$= qTotalPaper_{r,y} - (qKraftPulp_y + qSemiChemPulp_y + qTotalMechPulp_y) \qquad (280)$$

$$qPulpWash_{r,y} = prodcur_{ISX=7,r,y}$$

$$= qKraftPulp_{r,y} + qSemiChemPulp_{r,y} + qTotalMechPulp_{r,y} + qRecycledPulp_{r,y} \qquad (281)$$

$$qPulpDry_{r,y} \ = prodcur_{ISX=8,r,y} \ = \ qPulpWash_{r,y} \ = \ qTotalPaper_{r,y} \qquad (\,282\,)$$

$$qPulpBleach_{r,y} = \ prodcur_{ISX=9,r,y} \qquad (\,283\,)$$

where

$prodcur_{ISX=m,r,y}$	=	physical production flow for pulp and paper model step $ISX = m$, region r and year y;
$qWoodPrep_{r,y}$	=	quantity of wood in thousand tonnes processed in wood prep step for region r and year y;
$qKraftPulp_{r,y}$	=	quantity of pulp in thousand tonnes processed in Kraft process for region r and year y;
$qSemiChemPulp_{r,y}$	=	quantity of pulp in thousand tonnes processed in semi-chemical process for region r and year y;
$qMechPulp_{r,y}$	=	quantity of pulp in thousand tonnes processed in mechanical pulp process for region r and year y;
$qThermoMechPulp_{r,y}$	=	quantity of pulp in thousand tonnes processed in thermomechanical process for region r and year y;
$qRecycledPulp_{r,y}$	=	quantity of recycled pulp in thousand tonnes for region r and year y;
$qTotalPaper_{r,y}$	=	quantity of total paper produced, (paperboard, coated, uncoated, tissue, and newsprint) for region r and year y;
$qPulpWash_{r,y}$	=	quantity of pulp in thousand tonnes processed in pulp wash process step for region r and year y,
$qPulpDry_{r,y}$	=	quantity of pulp in thousand tonnes processed in pulp wash process step for region r and year y;
$qPulpBleach_{r,y}$	=	quantity of pulp in thousand tonnes processed in pulp wash process step for region r and year y;

Total paper physical flow is available, but paper is needed by specific product: newsprint, paperboard, coated paper, uncoated paper, and tissue paper. Subroutine PP_PROXY, which is described starting on page 197, computes product shares by year so that paper product production can be calculated. For example, the quantity of paperboard is defined by:

$$qPaperboard_{r,y} = \ prodcur_{ISX=12,r,y} = \ prodcur_{ISX=13,r,y} = \ prodcur_{ISX=14,r,y}$$

$$= PaperboardShare_y * qTotalPaper_{r,y} \ (\,284\,)$$

where

$qPaperboard_{r,y}$	=	total physical quantity of paperboard produced;
$PaperboardShare_y$	=	share of total paper production that is devoted to paperboard
$qTotalPaper_{r,y}$		is defined on page 173.

$prodcur_{ISX=12,r,y}$ = total physical quantity of paperboard processed in the drying process;

$prodcur_{ISX=13,r,y}$ = total physical quantity of paperboard processed in the finishing process; and

$prodcur_{ISX=14,r,y}$ = total physical quantity of paperboard processed in the stock prep process.

All paper types except newsprint have drying, finishing, and stock prep process. Newsprint has drying and finishing only.

Finally, the Kraft and semi-chemical pulping processes produce black liquor as a byproduct. These physical quantities are available nationally because the calculation is entirely within the pulp and paper model, which is a national model as follows:

$$qBlackLiquor_y = prodcur_{ISX=24,y} = prodcur_{ISX=25,y} = prodcur_{ISX=26,y} \qquad (285)$$

where

$qBlackLiquor_y$ = total black liquor available from the Kraft and semichemical pulping processes;

$prodcur_{ISX=24,y}$ = total physical quantity of black liquor processed in black liquor evaporators;

$prodcur_{ISX=25,y}$ = total physical quantity of black liquor associated with lime kiln processing; and

$prodcur_{ISX=26,y}$ = total physical quantity of black liquor processed in recovery furnaces.

The following sections describe the individual manufacturing processes addressed by the P&P Model. Each set of technology attributes is derived from the CIMS dataset. In some instances, the technology choice model considers a truncated subset of technologies, due to close similarity of costs and unit energy demands.

Wood Prep: isx = 1

The main operations employed for wood preparation include debarking, chipping, and conveying. Short logs are transported to pulping mills where the bark is treated with chemicals and in a rotating drum. The force of friction of bolts rubbing against each other and the edge of the drum removes the bark, which is then used as a fuel. In some cases, hydraulic debarking may be used, but this is more energy intensive. After debarking, the logs are chipped, most often in a radial chipper.

The physical output for this step, $SumProdCur_{ISX=1,y}$, is calculated by summing $prodcur_{ISX=1,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=1,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 57.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step as follows:

- ○ The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=1,f,Tech,y}$, is shown on page 150; and
- ○ The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=1,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=1,f,y}$, is shown on page 150.

Table 57. Wood prep (isx=1) base year technology shares and attributes

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)
Debarkers/cutters				
Ring style	94.9%	13,670	17.5	0.00
Rosser head	5.0%	13,670	17.5	0.00
Biodegradable	0.1%	33,820	10.2	0.00
Chippers				
Primary chip and saw	100.0%	--	89.45	--

Source: Consolidated Impacts Modeling System

In addition to the pulpwood produced in this process are waste and the combustible byproduct, hog fuel,[52] which is used to produce steam and electricity. The amount of hog fuel produced is calculated as follows:

$$HogFuel_y = Energy\_Use_{ISX=1,h,y}$$
$$= \left[(Hog\_Pulp * qVirginPulp_y) - qTotalPaper_y\right] * Hog\_Waste * Hog\_Heat \quad (286)$$

where

$Tot\_Energy\_Use_{ISX=1,h,y}$ = Energy use for hog fuel in the wood prep process in year ;

$HogFuel$ =   Combustible wood byproduct, in GJ;

$qVirginPulp_y = qKraftPulp_y + qSemiChemPulp_y + qTotalMechPulp_y$ virgin (nonrecycled) pulp in tonnes;

Hog_Pulp =   Tonnes of wood required for each tonne of pulp, from AFPA data;

Hog_Heat =   Heat content of hog fuel, in GJ per tonne, from MECS; and

Hog_Waste =   Percentage of wood waste that is allocated to hog fuel, calibrated so that 2014 totals comport with MECS estimates.

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[52] Hog fuel derives its name from the Norwegian word for *chopped* or *hacked*: *hogge*. Rest assured that no porcine units were injured in the making of this product.

The hog fuel created in this step is subsequently used to generate electricity and produce steam. The logic of the calculation is depicted below, and results from combining AFPA and PRODFLOW data to infer the production of hog fuel from the production of pulp.

Figure 26. Hog fuel created in this step and the logic of the calculation
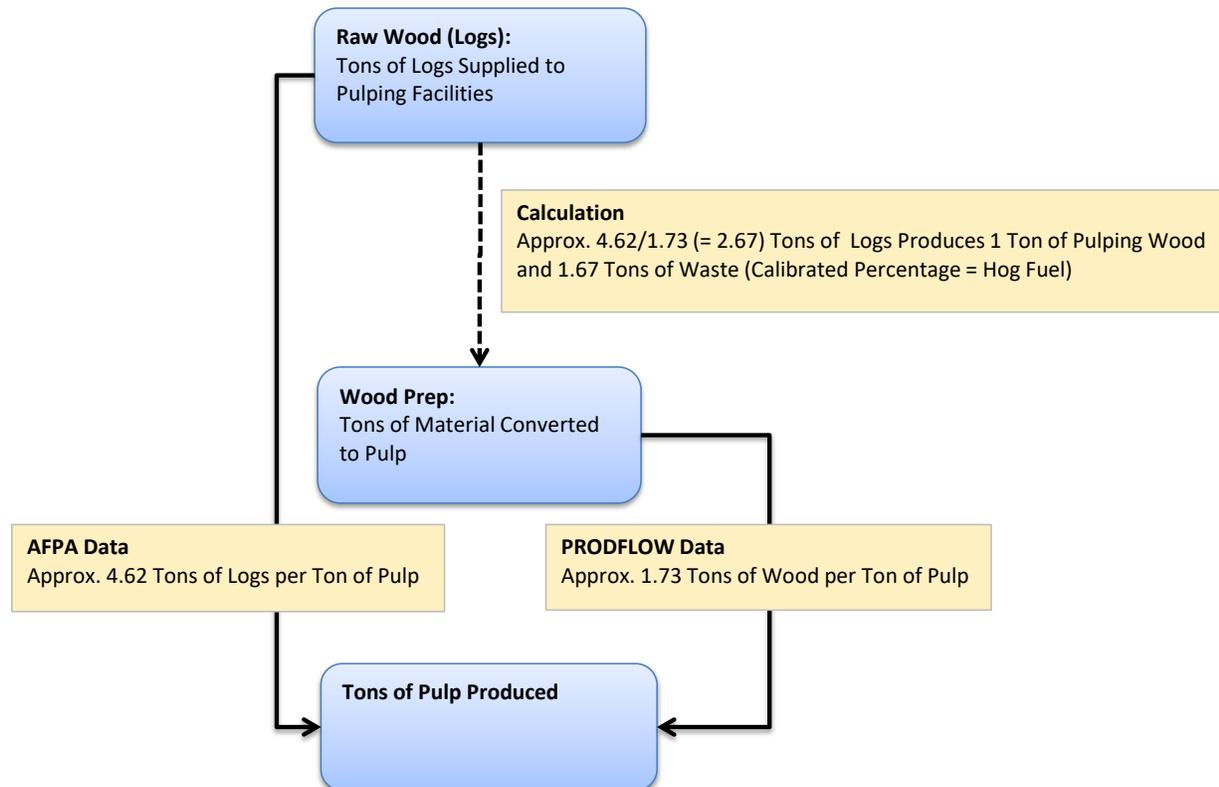
Kraft Pulp: isx = 2

The Kraft pulping process involves treating wood chips and sawdust with a sodium sulfide and sodium hydroxide solution that breaks the bonds that link lignin to the cellulose. The highly alkaline chemical and wood mixture is digested (or more simply, cooked) with steam under pressure. Digestion may be either a continuous process or treated in discontinuous batches.

The physical output for this step, $SumProdCur_{ISX=1,y}$, is calculated by summing $prodcur_{ISX=2,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=2,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel,

steam, and oxygen consumption can be calculated by technology. Energy, technology and oxygen characteristics are shown in Table 58.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step, as follows:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=2,f,Tech,y}$, is shown on page 150; and
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=2,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=1,f,y}$, is shown on page 150.

Table 58. Kraft pulping technologies and energy consumption

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Batch digester	9.0%	24,038	845	0.00	4,990
Batch with heat recovery	3.4%	24,531	845	0.00	4,758
Batch with heat recovery and computer control	5.0%	24,857	845	0.00	4,526
Batch with RDH superbatch	4.0%	25,376	845	0.00	3,655
Continuous digester	29.9%	23,259	1,088	0.00	3,733
Continuous with computer control	48.8%	23,583	1,088	0.00	3,653

Source: Consolidated Impacts Modeling System

For every tonne of Kraft pulp produced, a constant quantity of black liquor is produced as a byproduct. The black liquor is subsequently processed through lime kilns and evaporators and burned off in recovery furnaces, producing steam and electricity (details are available starting on page 188). The amount of black liquor produced is given as follows:

$$BLiquor_{isx=2,y} = \sum_{Tech} Tot\_Prod\_Tech_{Tech,y} * BLKLIQ_{isx=2} \qquad (\ 287\ )$$

where

$BLiquor_{isx=2,y}=$ Combustible Black Liquor, in GJ, from the Kraft process ISX=2; and

$BLKLIQ_{isx=2}$ = Conversion factor for the Kraft process in GJ/kilotonne, calibrated to ensure that 2014 values comport with those reported by MECS.

Semi-Chem Pulp: isx = 3

The neutral sulfite semi-chemical (NSSC) pulping process is used at a number of U.S. mills to produce courser-grade products such as corrugated board, which has a yield of about 75% of the wood raw material. In NSSC pulping, wood chips are softened by briefly cooking them in a neutral sodium or

ammonium sulfite solution and then separating the fibers in a refiner. Digestion may be either a continuous process or treated in discontinuous batches.

The physical output for this step, $SumProdCur_{ISX=3,y}$, is calculated by summing $prodcur_{ISX=3,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=3,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 59.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=3,f,Tech,y}$, is shown on page 150; and
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=3,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=3,f,y}$, is shown on page 150.

Table 59. Semi-chemical pulping technologies and energy consumption

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Batch digester	99.8%	20,192	1,998	0.00	1,799
Batch digester with heat recovery	0.1%	20,880	1,998	0.00	1,335
Continuous digester	0.1%	16,036	1,998	0.00	1,776

Source: Consolidated Impacts Modeling System

As with Kraft pulp, for every tonne of Semi-Chemical pulp produced, a constant quantity of Black Liquor is produced as a byproduct. This is subsequently processed through Lime Kilns and Evaporators, and burned off in Recovery Furnaces, producing steam and electricity. The calculation for the amount of Black Liquor produced in the semi-chemical process, $BLiquor_{isx=3,y}$ is the same as in the Kraft process and calculated on page 177.

Mechanical Pulp: isx = 4

The P&P model separates mechanical pulping processes into conventional mechanical pulping and thermomechanical pulping, which have different technology attributes. This division is based on historical data from AFPA[53] and projected using changes in production indexes of newsprint and tissue.

In the stone groundwood process, debarked short logs (roundwood) are fed into wet stone grinders by hydraulic rams. The abrasion of the grinding wheel against the wood physically separates the wood fibers. The grinding process usually is automatic and continuous. Refiner mechanical pulping (RMP) uses chips in lieu of roundwood and produces paper with higher strength than conventional groundwood because of less damage to the fibers in the pulping process.

The amount of mechanical pulp is calculated slightly differently from the other process steps.

The physical output for this step, $SumProdCur_{ISX=4,y}$, is calculated by summing $prodcur_{ISX=4,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=1,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 60.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=4,f,Tech,y}$, is shown on page 150; and
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=4,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=4,f,y}$, is shown on page 150.

Table 60. Mechanical pulping technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Stone grinder	25.7%	37,280	5,116	0.00	0
Mechanical refiner	3.3%	44,454	6,734	0.00	0
Size two refiner	49.6%	70,738	6,222	0.00	-2,500
Size two high speed refiner	21.4%	74,820	6,211	0.00	-2,500

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[53] American Forest & Paper Association, *2013 Statistical Summary of Paper, Paperboard, and Pulp*, Table 15.

In this process, a supply of steam is produced, which is used to offset steam demand in other processes. In contrast with Kraft and Semi-Chemical pulping processes, Mechanical processes do not produce black liquor as a byproduct.

Thermo-Mechanical Pulp: isx = 5

The thermomechanical process (TMP) was developed as a modification of the RMP process. In TMP, the wood chips are steamed for several minutes under pressure and subsequently refined in one or two stages. A further development of the thermo-mechanical pulp is CTMP pulp, in which the wood chips are impregnated with a chemicals treatment before the grinding. The refined wood pulp, although still weaker than chemical pulp, makes a stronger paper than conventional mechanical pulp with only a small sacrifice in yield, but with large energy requirements.

The physical output for this step, $SumProdCur_{ISX=5,y}$, is calculated by summing $prodcur_{ISX=5,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=5,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology and other characteristics are shown in Table 61.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=5,f,Tech,y}$, is shown on page 150; and
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=5,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=4,f,y}$, is shown on page 150.

Table 61. Thermo-mechanical pulping technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Chemical thermo-mechanical pulp (CTMP)	99.7%	74,277	6,222	0.00	0
Thermo-mechanical pulp (TMP)	0.3%	80,949	3,111	0.00	0

Source: Consolidated Impacts Modeling System

Recycled Pulp: isx = 6

Recycled pulp is manufactured from waste paper that is processed into paper stock. Pulping is accomplished through violent agitation and shearing action performed at high temperatures. Paper produced from recycled pulp is generally weaker than papers from virgin materials, because of the breakdown of the used fibers and loss of fiber bonding. Energy, technology, and other characteristics are shown in Table 62.

The physical output for this step, $SumProdCur_{ISX=5,y}$, is calculated by summing $prodcur_{ISX=6,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=6,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 61.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=6,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=6,Tech,y}$ is shown on page 150.
- o Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=4,f,y}$, is shown on page 150.

Table 62. Recycled pulp technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Recycled with deinking	99.8%	11,539	424	0.00	1,000
Recycled with flotation deinking	0.1%	65,218	1,037	0.00	913
Recycled with explosion eeinking	0.1%	74,633	318	0.00	750

Source: Consolidated Impacts Modeling System

Pulp Wash & Dry: isx = 7, 8

After pulping and bleaching, the pulp is blended with additives and processed into the stock that is used for paper manufacture. Before heat drying, pulps are sent to a pressing section to squeeze out as much water as possible though mechanical means. The pulp is compressed between two rotating rolls where the extent of water removal is dependent on the design of the machine and its running speed. When the pressed pulp leaves the pressing section, it has about 65% moisture content. In an integrated mill, this pulp is sent to the paper making section. In a non-integrated mill, the pulp is further dried so that it can

be baled for transportation to the next mill for paper manufacture. Such pulp, termed market pulp, is dried to about 10% moisture content in steam-heated dryers. Energy, technology, and other characteristics are shown in Table 63.

The physical output for this step, $SumProdCur_{ISX=k,y}$, = is calculated by summing $prodcur_{ISX=k,r,y}$ $k \in [7,8]$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=1,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 63.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=k,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=4,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption is calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=k,f,y}$, is shown on page 150.

Table 63. Pulp washing and drying technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Washing: isx = 7					
Drum washer	75.0%	15,123	348	0.00	0
Diffusion washer	25.0%	15,123	269	0.00	0
Drying: isx = 8					
Steam dryer	80.0%	26,320	838	0.00	5,440
Steam and electric vapor dryer	20.0%	30,992	1,072	0.00	5,040

Source: Consolidated Impacts Modeling System

Bleaching: isx = 9

Raw pulp still contains an appreciable amount of lignin and other discoloration. To produce light or white colors preferred for many products, it must be bleached. Bleaching is normally done in several stages. Chlorination and oxidation removes any residual lignin. A number of bleaching agents may be used and are applied in a stepwise fashion within a bleaching sequence. These include chlorine gas, chlorine dioxide, sodium hypochlorite, hydrogen peroxide, and oxygen. Energy, technology, and other characteristics are shown in Table 64.

The physical output for this step, $SumProdCur_{ISX=9,y}$, is calculated by summing $prodcur_{ISX=9,r,y}$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=9,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 60.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=9,f,Tech,y}$, is shown on page 150; and
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=9,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=4,f,y}$, is shown on page 150.

Table 64. Bleaching technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Chlorine Dioxide (ClO$_2$) bleach	60.4%	21,464	395	0.00	3,398
Hypochlorite bleach	0.1%	16,340	290	0.00	3,398
Hypochlorite bleach with computer control	0.1%	16,595	290	0.00	3,194
Oxy-delignification with first stage ClO$_2$	26.1%	25,950	536	0.00	3,748
Oxy-delignification with second stage ClO$_2$	13.4%	21,464	499	0.00	3,748

Source: Consolidated Impacts Modeling System

Papermaking

Each pulp product serves as the stock for many types of paper products. Newsprint can use feedstock from each of the pulping processes. Other paper products, including tissue paper, uncoated and coated paper, and paperboard are made from blends of different pulps and varying degrees of stock inputs. Total paper production, estimated in PRODCUR, is divided into the five paper product types according to the *Paper_Share* calculation in Subroutine PP_PROXY, which is described starting on page 197.

Newsprint: isx = 10, 11

The physical output for this step, $SumProdCur_{ISX=k,y}$, = is calculated by summing $prodcur_{ISX=l,r,y}$ $l \in$ [10,11] across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=1,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 65.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=k,f,Tech,y}$, is shown on page 150; and
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=4,Tech,y}$ is shown on page 150.

Table 65. Newsprint technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Newsprint Drying: isx = 10					
Electric paper dryer	10.0%	29,067	5,037	0.00	0
Steam dryer	89.8%	27,601	98	0.00	5,100
Steam dryer with computer control	0.1%	27,927	98	0.00	4,760
High intensity dryer	0.1%	16,532	98	0.00	4,845
Newsprint Form & Finish: isx = 11					
Press and finish	99.7%	74,984	1,460	0.00	0
Press and induction heat finish	0.1%	79,836	1,495	0.00	0
Nip press and finish	0.1%	79,369	1,460	0.00	-363
Nip press and induction heat finish	0.1%	84,967	1,495	0.00	-363

Source: Consolidated Impacts Modeling System

Paperboard: isx = 12, 13, 14

This segment includes corrugated cardboard and packaging materials. Energy, technology, and other characteristics are shown in Table 66.

The physical output for this step, $SumProdCur_{ISX=k,y}$, is calculated by summing $prodcur_{ISX=m,r,y}$ $m \in [12,14]$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=1,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen,

fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 66.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=m,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=m,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=k,f,y}$, is shown on page 150.

Table 66. Paperboard technologies

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Drying: isx = 12					
Steam dryer	99.7%	24,770	43	0	10,200
Steam with computer control	0.1%	25,068	43	0	9,520
Steam with vapor recovery	0.1%	25,068	64	0	9,051
High intensity steam	0.1%	14,836	43	0	9,690
Form Press and Finish: isx = 13					
Form press and finish	99.7%	60,847	610	0	0
Form nip press and finish	0.1%	64,503	610	0	-363
Efficient press and finish	0.1%	76,769	569	0	0
Efficient nip press and finish	0.1%	80,425	593	0	-363
Stock Prep: isx = 14					
Conical refine and screen	80.0%	23,104	497	0	0
Disc refine and screen	20.0%	32,626	336	0	0

Source: Consolidated Impacts Modeling System

Coated Paper: isx = 15, 16, 17

Coating is a process by which paper or board is coated with an agent to improve brightness or printing properties. By applying precipitated calcium carbonate (PCC), china clay, pigment or adhesive, the coating fills the miniscule pits between the fibers in the base paper, giving it a smooth, flat surface, which can improve the opacity, luster, and color-absorption ability. [54] Energy, technology, and other characteristics are shown in Table 67.

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[54] http://www.paperonline.org/paper-making/paper-production/paper-finishing/coated-or-uncoated

The physical output for this step, $SumProdCur_{ISX=u,y}$, is calculated by summing $prodcur_{ISX=u,r,y}$ $u \in$ [15,17] across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=u,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=u,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=u,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=u,f,y}$, is shown on page 150.

Table 67. Coated paper technologies, energy consumption, and non-energy characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Drying: isx = 15					
Steam dryer	99.7%	31,980	117	0.00	8,160
IR radiation dryer	0.1%	34,551	3,984	0.00	0
High intensity steam	0.1%	19,155	117	0.00	7,752
High intensity electric	0.1%	19,731	3,791	0.00	0
Form Press and Finish: isx = 16					
Form press and finish	99.7%	84,098	788	0.00	0
Form nip press and finish	0.1%	89,055	788	0.00	-363
Efficient press and finish	0.1%	105,686	723	0.00	0
Efficient nip press and finish	0.1%	110,643	762	0.00	-363
Stock Pre: isx = 17					
Disc refine and screen	99.9%	23,104	758	0.00	0
Efficient Disc Refine & Screen	0.1%	32,626	516	0.00	0

Source: Consolidated Impacts Modeling System

Uncoated Paper: isx= 18, 19, 20

Not all paper is coated. Uncoated paper is typically used for letterheads, copy paper, or printing paper. Most types of uncoated paper are surface sized to improve their strength. Such paper is used in stationery and lower quality leaflets and brochures. [55]

The physical output for this step, $SumProdCur_{ISX=k,y}$, = is calculated by summing $prodcur_{ISX=v,r,y}$ $v \in$ [18,20] across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=v,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 68.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=v,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=v,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=v,f,y}$, is shown on page 150.

Table 68. Uncoated paper technologies, energy consumption, and non-energy characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Drying: isx = 18					
Steam dryer	99.7%	31,980	117	0.00	8,160
IR radiation dryer	0.1%	32,406	117	0.00	7,616
High intensity steam	0.1%	19,155	117	0.00	7,752
Steam with high humidity hood	0.1%	33,899	117	0.00	7,507
Form Press and Finish: isx = 19					
Form press and finish	99.7%	84,098	788	0.00	0
Form nip press and finish	0.1%	89,055	788	0.00	-363
Efficient Press & Finish	0.1%	105,686	723	0.00	0
Efficient Nip Press & Finish	0.1%	110,643	761	0.00	-363
Stock Prep: isx = 20					
Conical refine and screen	99.9%	23,104	758	0.00	0
Efficient disc refine and screen	0.1%	32,626	516	0.00	0

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[55] http://www.paperonline.org/paper-making/paper-production/paper-finishing/coated-or-uncoated

Source: Consolidated Impacts Modeling System

Tissue Paper: isx = 21, 22, 23

This segment covers a wide range of tissue and other hygienic papers for use in households or on commercial and industrial premises. Examples are toilet paper and facial tissues, kitchen towels, hand towels and industrial wipes.

Not all paper is coated. Uncoated paper is typically used for letterheads, copy paper, or printing paper. Most types of uncoated paper are surface sized to improve their strength. Such paper is used in stationery and lower quality leaflets and brochures. [56]

The physical output for this step, $SumProdCur_{ISX=k,y}$, = is calculated by summing $prodcur_{ISX=w,r,y}$ $w \in [18,19,20]$ across regions in subroutine PP_Prodcur_Breakout, which is very similar to IS_PRODCUR breakout (see page 135). Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $SumProdCur_{ISX=v,y}$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 69.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=w,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=w,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=w,f,y}$, is shown on page 150.

Table 69. Tissue paper technology characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Drying: isx = 21						
Steam dryer	99.8%	24,907	4,062	450	0.00	2,856
Steam dryer with computer control	0.1%	25,206	3,791	450	0.00	2,666
Steam with high humidity hood	0.1%	26,401	3,737	450	0.00	2,628
Form Press and Finish: isx = 22						

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[56] http://www.paperonline.org/paper-making/paper-production/paper-finishing/coated-or-uncoated

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Form press and finish	99.9%	74,495	0	1,747	0.00	0
Efficient press and finish	0.1%	93,119	0	1,405	0.00	0
Stock Prep: isx = 23						
Conical refine and screen	80.0%	23,104	0	1,840	0.00	0
Efficient disc refine and screen	20.0%	32,626	0	1,248	0.00	0

Source: Consolidated Impacts Modeling System

Chemicals Recovery

Pulp mills commonly employ a chemical recovery processes to reclaim spent chemicals from the pulping process. The most common is spent cooking liquor, referred to as weak black liquor, from the pulp washers is routed to a chemical recovery process that involves concentrating the weak black liquor, combusting organic compounds, reducing inorganic compounds, and reconstituting the cooking liquor. The weak black liquor is first directed through a series of evaporators to increase the solids content to about 50% to form strong black liquor. The strong black liquor is further concentrated in a direct or non-direct contact evaporators, also called concentrators.

Evaporators: isx = 24

Black Liquor is a byproduct that flows from the Kraft and Semi-chemical pulping steps, above. This byproduct flows to Evaporators, Recovery Furnaces, and finally, in the form of Green Liquor, to Lime Kilns. The P&P model generates material flows of Black Liquor solids in units of GJ, not mass or volume, and the following processes to treat Black Liquor are based on an implicit (and constant) level of dilution. The conversion factor that specifies the amount of Black Liquor generated by the pulping processes has been calibrated so as to comport with the 2014 MECS estimate. The total flow of Black Liquor to evaporators is given as follows:

$$qBlackLiquor_y = \sum_{isx=2}^{3} BLiquor_{isx,y} \qquad\qquad (288)$$

where

$BLiquor_{isx}$ = Quantity of Black Liquor solids, in GJ, produced in the Kraft and Semi-Chemical pulping processes (*isx = 2, 3*), which is defined on page 177.

Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $qBlackLiquor_y$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen

consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 70.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=24,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=24,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=24,f,y}$, is shown on page 150.

Table 70. Black liquor evaporator technologies, energy consumption, and non-energy characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Basic evaporator	16.0%	9,635	46	0.00	4,219
Evaporator with computer control	50.0%	9,751	46	0.00	4,159
Evaporator with standalone concentrator	10.0%	10,599	46	0.00	3,840
Evaporator with integrated concentrator	24.0%	10,117	46	0.00	2,700

Source: Consolidated Impacts Modeling System

Lime Kilns: isx = 25

This process step treats the green liquor produced by the recovery furnace through the addition of lime (CaO) to convert the Na2CO3 into sodium hydroxide (NaOH). Following treatment, CaCO3 is collected as a precipitate, which is washed, dried, and calcined in a lime kiln to produce CaO, which is then recycled. Although it is green liquor, not black liquor that is treated in lime kilns, the relationship is considered constant and the kiln technology characteristics are linked to black liquor flows.

Total flow of black liquor to evaporators is the same as the total flow of Black Liquor to Recovery Furnaces, which is defined on page on page 190. Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $qBlackLiquor_y$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc (see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 71.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

○ The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=25,f,Tech,y}$, is shown on page 150.

○ The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=25,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fossil fuels and electricity can be calculated: $Tot\_Energy\_Use_{ISX=25,f,y}$, is shown on page 150.

In addition to fossil fuels and electricity, lime kilns also use wood waste. Energy use is computed for separately, as follows:

$$Wood\_Kiln_y = EnergyUse_{ISX=25,f=hogfuel,y} = \sum_{Tech} Tot\_Prod\_Tech_{Tech,y} * H\_Fuel_{Tech} \quad (289)$$

where

$Wood\_Kiln$ = Quantity of Hog Fuel, in GJ, used in lime kilns; and

H_Fuel_{Tech} = Energy intensity of wood waste, in GJ/kT, for lime kilns technology Tech.

Table 71. Lime kiln technologies, energy consumption, and non-energy characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Natural gas (million British thermal units per kilotonne)	HFO (million British thermal units per kilotonne)	Electricity (million British thermal units per kilotonne)	Coal (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Hog fuel (gigajoules per kilotonne)
Basic natural gas lime kiln	69.8%	1,767	1,266	0	21	0	66	0
Natural gas kiln with flash dryer	29.9%	1,767	877	0	21	0	46	0
Oil kiln with flash dryer	0.1%	1,767	0	863	21	0	66	0
Coal kiln with flash dryer	0.1%	11,656	219	0	21	757	12	0
Oil and wood waste kiln	0.1%	11,656	0	216	21	0	17	797

Source: Consolidated Impacts Modeling System

Recovery Furnaces: isx = 26

The recovery furnace functions to combust all organic compounds in the black liquor and to reduce all Na2SO4 to Na2S. Concentrated black liquor is sprayed into the recovery furnace where organic compounds are combusted. Molten inorganic salts, referred to as smelt, collect in a char bed at the bottom of the furnace. Smelt is drawn off and dissolved in weak wash water in the smelt dissolving tank to form a solution of carbonate salts called green liquor, which is primarily Na2S and Na2CO3.

Total flow of black liquor to evaporators is the same as the total flow of Black Liquor to Recovery Furnaces, which is defined on page 190. Subroutine Step_Capacity (see page 102) calculates how much additional productive capacity, if any, is needed to produce the physical output equal to $qBlackLiquor_y$. Once any additional productive capacity has been calculated, the subroutine Logit_Calc

(see page 104) chooses the technologies for the added capacity. Once technologies for the new capacity are chosen, fossil fuel, steam, and oxygen consumption can be calculated by technology. Energy, technology, and other characteristics are shown in Table 72.

Fossil fuel consumption is calculated for each technology as it is for the Blast Furnace/Basic Oxygen Furnace step:

- o The calculation for energy use by fuel, technology, and year, $Energy\_Use_{ISX=26,f,Tech,y}$, is shown on page 150.
- o The calculation for quantity of steam demanded by fuel, technology, and year, $Steam\_Dmd_{ISX=26,Tech,y}$ is shown on page 150.

Once fossil fuel and electricity consumption are calculated by technology, energy use by fuel can be calculated: $Tot\_Energy\_Use_{ISX=26,f,y}$, is shown on page 150.

Table 72. Recovery furnace technologies, energy consumption, and non-energy characteristics

Technology	Tech share (base year)	Fixed costs (dollars per kilotonne)	Electricity (million British thermal units per kilotonne)	CO2 emissions (tons per kilotonne)	Steam use (gigajoules per kilotonne)
Furnace with 600 psig cogeneration	17.4%	24,175	-781	0	-6,950
Furnace with direct contact evaporator	15.9%	22,526	111	0	-5,600
Furnace with low odor configuration	42.0%	22,526	111	0	-6,500
Furnace with low odor configuration and computer control	4.5%	22,526	111	0	-6,600
Furnace with high solids firing	4.5%	23,652	111	0	-6,950
Furnace with 900 psig cogeneration	15.6%	23,987	-1,074	0	-6,950

Source: Consolidated Impacts Modeling System

Steam and Electric Power Generation

Pulp and paper mills use spent steam from on-site CHP units as a source of heat for their processes such as pulping (pulp cooking) and pulp and paper drying. CHP units are rapidly replacing traditional boilers because of their added benefit of producing electricity as well. Steam is needed to cook the pulp and dry wet paper on the paper machines. Instead of producing steam at a wide range of pressures needed for the different unit operations, high pressure steam is generated in a boiler and run through a turbine to generate electric power. The lower pressure steam that exits the turbines is then used throughout the P&P plant for all heating needs.

This set of calculations is intended to be used in place of the boiler, steam, and cogeneration (BSC) component of the IDM, and the results have been calibrated to comport with the 2014 MECS estimates. Following this section is a series of notes that describe the rationale and approach to this calibration.

The first step in this section is to estimate the total process steam that needs to be generated to meet the steam demand of the preceding process steps 1 through 25:

$$Proc\_Steam_y = (1.0 - Recycle\_Pct) * \left(\sum_{isx=1}^{25} \sum_{Techi=1}^{Maxi} Steam\_Dmd_{Techi,isx,y} \right) \qquad (\,290\,)$$

where

$Proc\_Steam_y$ = Quantity of process steam, in GJ, required for all P&P processes, excluding black liquor recovery furnaces;

$Recycle\_Pct$ = Share of generated steam that is recycled for low-intensity applications, calculated through offline analysis to be 34%;

$Techi$ = Process technology index for step *isx;* and

$Maxi$ = Maximum number of technology choices for step *isx.*

This calculation represents the process steam required in the first 25 steps, but it does not include the offsetting impact of steam produced by the black liquor recovery furnaces (*isx = 26*), described above. This quantity is redefined as follows:

$$BL\_Steam_y = -\left(\sum_{Tech=1}^{Maxi} Steam\_Dmd_{Tech,isx=26,y} \right) \qquad (\,291\,)$$

where

BL_Steam = Quantity of steam, in GJ, produced by black liquor recovery furnaces, in year *y* expressed as a negative demand.

From this is subtracted the steam generated by hog fuel and black liquor recovery furnaces (*isx = 26*) to obtain net steam produced by fossil fuels, as follows:

$Net\_Proc\_Steam_y$

$$= BTU\_Conv * \left[Proc\_Steam_y + BL\_Steam_y - Net\_HogFuel_y * Bio\_Eff \right] \qquad (\,292\,)$$

where

$Net\_Proc\_Steam_y$ = Quantity of process steam, in MMBtu, produced by fossil fuels; and

$BTU\_Conv =$ unit conversion constant that converts gigajoules to MMBtu, defined on page 162.

$HogFuel_y$ = Combustible wood waste produced by the Wood Prep step (*isx = 1*), in GJ defined on page 175;

$Wood\_Kiln_y$ = Amount of Hog Fuel consumed by Lime Kilns (*isx = 25*), in GJ, defined on page 190;

$Net\_HogFuel_y = HogFuel_y - Wood\_Kiln_y$ = Hog Fuel available to generate steam in CHP systems, in GJ; and

Bio_Eff = Boiler efficiency of biofuels, set in the IDM at 69%.

The net process steam is then allocated between conventional boilers and CHP systems as follows:

$$Steam\_Boil_y = Net\_Proc\_Steam_y * Boil\_Shr_y \qquad (300)$$

$$Steam\_CHP_y = Net\_Proc\_Steam_y * (1.0 - Boil\_Shr_y) \qquad (293)$$

where

$Steam\_Boil_y$	=	Quantity of process steam, in GJ, produced in boilers in year y;
$Steam\_CHP_y$	=	Quantity of process steam, in GJ, produced in CHP systems in year y; and
$Boil\_Shr_y$ =	=	Share of total net process steam produced in boilers in year y, set at 32% in 2015, and declining linearly to 20% in 2050.

The demand for fossil fuels in boilers is calculated as follows:

$$Boil\_Fuel\_Dmd_{f,y} = Steam\_Boil_y * Boil\_FShare_f * Boil\_Eff_f \qquad (294)$$

where

$Boil\_Fuel\_Dmd_{f,y}$	=	Demand for fossil fuels in boilers (GJ) for process for fuel f and year y;
$Boil\_Eff_f$	=	Boiler energy intensity, in GJ of fuel input / GJ of steam output for fossil fuels natural gas, oil, and coal; and
$Boil\_FShare_{f,y}$	=	Allocation of steam production among fossil fuels for process for fuel f and year y.

The boiler characteristics, obtained from CIMS data, are provided below. The fuel shares have been calibrated to comport with MECS 2014 estimates.

Table 73. Pulp and paper fossil fuel-fired boiler information

Fuel	Fossil fuel shares (Boil_Fshare)		Energy intensity (gigajoules fuel per gigajoules steam) (Boil_Eff)
	2015	2050	
Natural gas	59%	84%	1.25
Oil	1%	1%	1.25
Coal	40%	15%	1.23

Source: Consolidated Impacts Modeling System

Similarly, the demand for fossil fuels in CHP systems is given as follows:

$$CHP\_Fuel\_Dmd_{f,y} = Steam\_CHP_y * CHP\_FShare_f * CHP\_Eff_f \qquad (295)$$

The electricity generated by these systems is given as follows:

$$CHP\_Elec_{f,y,f} = Steam\_CHP_y * CHP\_FShare_f * CHP\_EIntens_f \qquad (296)$$

where

$CHP\_Eff_{f,y}$ = CHP energy intensity, in GJ of fuel input / GJ of steam output for fossil fuel f (NG, Oil, and coal) and year $y \in [2015, 2050]$;

$CHP\_EIntens_{f,y}$ = CHP electric intensity, in GJ of fuel input / GJ of electricity output for fossil fuel f and year y

$Boil\_Fuel\_Dmd_{f,y}$ = Demand for fossil fuels in boilers (GJ) for fuel f and year y;

$CHP\_Elec_{f,y}$ = Electricity generated by CHP systems, in GJ, for fossil fuel f and;

$CHP\_Fuel\_Dmd_f$ = Demand for fossil fuels in CHP systems for fossil fuel , in GJ; and

CHP_FShare_f = Allocation of steam production among for fossil fuel f.

The characteristics of CHP systems, obtained from CIMS data, are provided below. As with boiler systems, the fuel shares remain constant, but the energy intensities change over time to reflect assumed transitions to more advanced CHP systems.

Table 74. Pulp and paper fossil fuel-fired CHP intensity, 2015 and 2050.

Fuel	Fossil fuel shares (CHP_Fshare)		Energy intensity, fuel (gigajoules fuel per gigajoules steam) (CHP_Eff)		Energy intensity, electricity (gigajoules electricity per gigajoules steam) (CHP_EIntens)	
	2015	2050	2015	2050	2015	2050
Natural gas	54%	80%	1.40	1.41	-0.117	-0.121
Oil	3%	3%	1.40	1.40	-0.111	-0.111
Coal	43%	17%	1.37	1.37	-0.111	-0.111

Source: Consolidated Impacts Modeling System

Added to the electricity generated by fossil fuels is that generated by Black Liquor and Hog Fuel, as follows:

$CHP\_Elec_{Bio,y}$

$$= (Net\_HogFuel_y * Bio\_Eff + BL\_Steam_y) * CHP\_EIntens_{Bio} \qquad (297)$$

where

$CHP\_Elec_{Bio,y}$ = Electricity generated by CHP systems from biofuels Bio, in GJ; and

$CHP\_EIntens_{Bio}$ = CHP electric intensity, in GJ of electricity / GJ steam for biofuels, set at the CIMS value of -0.138.

The total electricity generated by CHP systems is then calculated as follows:

$$Tot\_CHP\_Elec_{f,Bio,y} = CHP\_Elec_{Bio,y} + \sum_f CHP\_Elec_{f,y} \qquad (298)$$

Summary of Energy Demand

The final step in the P&P model is to first add up fuel demands for each process step across all technologies, as follows:

$$Total\_Energy\_Use_{isx,f,y} = \sum_{Tech\ =1}^{Max\_Tech} Energy\_Use_{isx,f,y,Tech}\ * BTU\_Conv \qquad (\ 299\ )$$

Then the P&P model ends with summing across all process steps and add boiler and CHP consumption, as follows:

$$Total\_Q_{f,y} = Boil\_Fuel\_Dmd_{f,y} + CHP\_Fuel\_Dmd_{f,y} + \sum_{isx=1}^{26} Total\_Energy\_Use_{isx,f,y} \qquad (\ 300\ )$$

where

BTU_Conv = Conversion factor to convert GJ to trillion Btu;

$Total\_Energy\_Use_{isx,f,y}$ = Total demand for energy, by fuel f, within each process step (GJ) and year y; and

$Total\_Q_{f,y}$ = Total demand for energy, by fuel, for the P&P model.

Unique paper module subroutines and notes

Subroutine PP_PROXY

The macroeconomic model provides estimates of the total production of paper, but does not break out all the components of this production. Because there are different technologies and processes involved in producing different types of paper products, the pulp and paper model constructs a set of normalized indexes to allocate total paper production among five product types: (1) newsprint, (2) paperboard, (3) coated paper, (4) uncoated paper, and (5) tissue. These indexes are based on macroeconomic model estimates of the following sectors' output.

Table 75. Macro model sector outputs

NAICS code	Industries	PP_Proxy_x
3221	Pulp, Paper, & Paperboard Mills	PP_Proxy_1
32221	Paperboard Container Manufacturing	PP_Proxy_2
322x	All other NAICS 322 Categories	PP_Proxy_3
323	Printing & Related Support	PP_Proxy_4
5111	Newspapers, Periodicals, & Books	PP_Proxy_5

For each product type (*prx*), a production index is defined as follows:

Newsprint ($prx = 1$):

$$PP\_ProdNDX_{prx=1,y} = \frac{PP\_Proxy\_4_y/PP\_Proxy\_5_y}{PP\_Proxy\_4_{Base}/PP\_Proxy\_5_{Base}}$$ (301)

Paperboard ($prx = 2$):

$$PP\_ProdNDX_{prx=2,y} = \frac{PP\_Proxy\_2_y/PP\_Proxy\_1_y}{PP\_Proxy\_2_{Base}/PP\_Proxy\_1_{Base}}$$ (302)

Coated paper ($prx = 3$):

$$PP\_ProdNDX_{prx=3,y} = \frac{PP\_Proxy\_4_y/PP\_Proxy\_1_y}{PP\_Proxy\_4_{Base}/PP\_Proxy\_1_{Base}}$$ (303)

Uncoated paper ($prx = 4$):

$$PP\_ProdNDX_{prx=4,y} = PP\_ProdNDX_{3,y} \quad\quad\quad (304)$$

Tissue paper $(prx = 5)$:

$$PP\_ProdNDX_{prx=5,y} = \frac{PP\_Proxy\_3_y/PP\_Proxy\_2_y}{PP\_Proxy\_3_{Base}/PP\_Proxy\_2_{Base}} \quad\quad (305)$$

where

$PP\_Proxy_{r\ y}$ = The value of industrial output in the associated industry, r, from the Macroeconomic model for year y;

$Base$ = The base year relative to which changes are measured, corresponding to the most recent year of production data from the American Forest Product Association (AFPA) survey (2013); and

$PP\_ProdNDX_{prx,y}$ = Production index reflecting change in production shares of each paper type (prx) for year y relative to the base year of 2013.

Next, a temporary, un-normalized estimate of paper production shares is calculated as follows:

$$Paper\_Temp_{prx,y} = PP\_ProdNDX_{prx,y} * Paper\_Share_{prx,Base} \quad\quad (306)$$

where

$Paper\_Share_{prx,Base}$ = The base year (2013) shares of total paper production for product prx, according to the AFPA survey.

The normalized shares are subsequently calculated:

$$Paper\_Share_{prx,y} = \frac{Paper\_Temp_{prx}}{\sum_{prx=1}^{5} Paper\_Temp_{prx}} \qu\quad\quad (307)$$

Mechanical Pulping Allocation

Mechanical Pulping is another step in which greater detail is required. There are two processes to consider: conventional mechanical pulping and thermomechanical pulping. The former is used primarily for such products as newsprint, while the latter is used mainly in the production of tissue. The model uses the proxy indexes described above to estimate the shares of mechanical pulp attributable to the two processes. The base-year share is obtained from AFPA data in 2013. The shares of mechanical pulp attributable for the processes are calculated as follows:

$Mech\_Share_y$

$$= Mech\_Share_{y-1} * \left[\frac{PP\_ProdNDX_{1,y} \Big/ \left(PP\_ProdNDX_{1,y} + PP\_ProdNDX_{5,y}\right)}{PP\_ProdNDX_{1,y-1} \Big/ \left(PP\_ProdNDX_{1,y-1} + PP\_ProdNDX_{5,y-1}\right)} \right] \quad (\,308\,)$$

Essentially, this process assumes that the marginal change in mechanical pulping share is equal to the marginal change newsprint's share of newsprint and tissue paper.

Note on Internal Benchmarking
The P&P model relies on process steps and data defined by CIMS, and efforts have been made to calibrate the results of this model to comport with MECS 2014 estimates of energy consumption in the paper industry. These efforts have required some minor adjustments to energy intensity figures used in the calculations and changes in the mix of boiler types used to produce steam. The following notes describe the process used in calibrating the model's results.

- o In MECS, *Net Demand for Electricity* represents total electricity consumed, whether produced off-site or on-site. All electricity consumed from the Wood Prep step through the Evaporator step is added and compared with the MECS 2014 figure. Using CIMS technology data, the model underestimates the MECS figure by approximately 2.7%. Accordingly, this factor is used to boost the electricity UEC's for all the technologies uniformly, before the tech-choice calculation. This factor is expressed as a variable in the input file, EL_ADJ, so it can be revised as necessary.
- o Net Electricity represents only that electricity produced from outside sources. The difference is internally-produced and is assumed to be all CHP; some produced by biofuels (Black Liquor & Hog Fuel), and the remainder produced by conventional fuels (HFO, NG, & Coal).
- o Black Liquor and Hog Fuel production is determined by the model & benchmarked to MECS by adjusting CIMS coefficients for Black Liquor production in the Kraft and Semi-Chemical pulping processes and by inferring the percentage of Wood Prep waste that is recovered as Hog Fuel. The Hog Fuel (in excess of that demanded by Lime Kilns) is used to produce steam at a 69% efficiency (from the IDM), which offsets steam demand from other processes and is also used for electricity generation. A similar approach is used with the Black Liquor Recovery Furnace, where steam production is determined by CIMS technology data.
- o The remaining steam demanded by the various processes is produced by conventional fuels in either CHP systems or boilers. Some of the steam is assumed to be recycled, reducing the demand for conventional fuels—the percentage of recycled steam is set to a fixed value, and the mix of boiler types is manually adjusted so that total conventional fuel consumption comports with MECS figures.

Appendix A. Model Abstract

Model name: Industrial Demand Module

Model acronym: IDM

Description:

The Industrial Demand Module is based upon economic and engineering relationships that model industrial sector energy consumption at the census division level of detail. The seven most energy-intensive industries are modeled at the detailed process step level and eight other industries are modeled at a less-detailed level. The IDM incorporates three components: buildings; process and assembly; and boiler, steam, and cogeneration.

Purpose of the model:

As a component of the National Energy Modeling System integrated modeling tool, the IDM generates long-term projections of industrial sector energy consumption. The IDM facilitates policy analysis of energy markets, technological development, environmental issues, and regulatory development as they affect industrial sector energy consumption.

Most recent model update:

December 2017

Part of another model:

National Energy Modeling System (NEMS)

Model interfaces:

The Industrial Demand Module receives inputs from the Electricity Market Module (EMM), Natural Gas Transmission and Distribution Module (NGTDM), Oil and Gas Supply Module (OGSM), Renewable Fuels Module (RFM), Macroeconomic Activity Module (MAM), Transportation Demand Module (TDM), Commercial Demand Module (CDM), and Liquid Fuels Market Module (LFMM).

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Documentation:

Model Documentation Report: Industrial Demand Module of the National Energy Modeling System, January 2018.

Archive media and installation manual(s):

The model is archived as part of the National Energy Modeling System production runs used to generate AEO2016.

Energy system described:

Domestic industrial sector energy consumption.

Coverage:

Geographic: Nine census divisions: New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific.

Time Unit/Frequency: Annual, 2014 through 2050.

Modeling features:

Structure: 15 manufacturing and 6 non-manufacturing industries. The manufacturing industries are further classified as energy-intensive or non-energy-intensive industries.

Each industry is modeled as three separate but interrelated components consisting of the process and assembly component (PA), the buildings component (BLD), and the boiler, steam, and cogeneration component (BSC).

Modeling Technique: The energy-intensive industries are modeled either through the use of a detailed process flow with technology diffusion or end-use accounting procedure. The remaining industries use the same general procedure but do not include a detailed process flow.

Non-DOE input sources:

- Historical Dollar Value of Shipments in the Industrial Sector
- Energy Expenditures in the Agriculture and Construction sectors
- Energy Consumption in the Mining sector
- Physical inputs of cement, glass, paper, iron & steel, and paper
- Consolidated Impact Modeling System (CIMS)

DOE input sources:

- Form EIA-923 and predecessor forms: Annual Electric Generator Report
- Form EIA-860 and predecessor forms: Annual Electric Generator Report
- Electricity generation, total and by prime mover
- Electricity generation for own use and sales

- Capacity utilization
- Manufacturing Energy Consumption Survey 2014, October 2017
- State Energy Data System 2012, June 2013
- Monthly Energy Review, (annual data 2012) September 2013

Computing environment:

Hardware Used: Intel Xeon CPU

Operating System: Microsoft Windows 7

Language/Software Used: Intel Visual Fortran 11.1

Estimated Run Time: approximately one minute for a 2014-2050 run in non-iterating, stand-alone mode.

Special Features: None

Appendix B. Data Inputs and Input Variables

Industrial demand module exogenous input files

The following input files are used by the Industrial Demand Module (IDM) along with their associated subroutines. The subroutines that read in the files are provided along with the update schedule. The following sections provide more detail on each of the currently used input files. Accompanying this list are the input data that a user can use to run the IDM.

Table B-1. Input files

File name	Description	Subroutine where read occurs	Update schedule
ethanereg.csv	Fraction of ethane feedstock consumed in each census division by year, from 1990 to four years after the last STEO year	READ_ETH_FRAC	Annual
enprod.txt	Production, energy, and byproduct data.	IRHEADER, IRBSCBYP, IRSTEPBYP	Update with MECS
exstcap.txt	Cogeneration history data on capacity, generation, and fuel consumption.	IRCOGEN	Full AEO (even model year)
feedstkaer.csv	Historical feedstock values for natural gas, naphtha, and hydrocarbon gas liquids from 1990–2005.	READ_FEEDSTOCK_AER	Annual
feedstock.csv	Historical and projected feedstock values for natural gas, naphtha, and hydrocarbon gas liquids from 2006 through the year after the last STEO year.	READ_FEEDSTOCK	Annual
ibfactri.csv	Benchmark factors only used in the benchmark side case.	IRSTEO	Annual
indbeu.txt	Industrial building energy use input.	ISEAM	Update with MECS
indcment.txt	This input file contains data for cement, aluminum, and glass submodules, and for coal mining.	READ_IDMINPUT	As needed
indcogen.xml	Cogeneration input data.	COGENT	As needed
indlime.txt	Lime production inputs.	READ_LIME	As needed
indmotor.xml	These data are used in the motors subroutine that is only called for Food (7), Chemicals (9), and all industries with an industry code of 14 or higher.	MOTORS	As needed
indrun.txt	Industrial model control file.	RCNTL	As needed
indsteo.txt	File containing STEO history and projections.	IRSTEO	Annual
ironstlx.xlsx	This input file contains data for iron and steel, and pulp and paper submodules.	IS_GETDATA	As needed
itech.txt	UECs and TPCs from MECS.	UECTPC	Update with MECS
itlbshr.txt	Boiler elasticities and the latest MECS BSC (Boiler Steam Component) fuel totals.	RCNTL	Update with MECS
plancap.txt	Cogeneration planned capacity values.	IRCOGEN	Annual
prodflow.txt	Data on production flow rates by process assembly steps, retirement rates, and reporting.	MECSBASE	Review with MECS update

File name	Description	Subroutine where read occurs	Update schedule
propanereg.csv	Fraction of industrial propane feedstock consumed in each census division by year, from 1990 to four years after the last STEO year	READ_PROP_FRAC	Annual

Buildings data - INDBEU.txt

This input file is energy use data for buildings associated with the manufacturing industries, which excludes non-manufacturing industries (ID from 1 to 6). Data include building energy use for lighting, heating, ventilation and air conditional as well as onsite transportation. After reading in the data, building energy use is converted from trillion Btu to trillion Btu per million employees.

Table B-2. INDBEU.txt inputs

Input data	Description	Units
Inpind	industry id for: Food (7), Paper (8), BChem (9), Glass (10), Cement (11), Steel (12), Aluminum (13), Fabmet (14), Machinery (15), Computer (16), TranEqp (17), Electrical (18), WoodPr (19), Plastic (20), BOMOth (21)	Integer
Dumc	Industry label read in as a dummy value that is not used	Character*15
Inpreg	Region ID	Integer
enbint(1,1)	Lighting: electricity	Real: trillion Btu
enbint(2,1:3)	HVAC: electricity, natural gas, steam	
enbint(3,1:2) enbint(3,4:5)	Onsite transportation: electricity, natural gas	
enbint(3,4:5)	Onsite transportation: distillate, LPG	
enbint(4,1:2)	Facility support: electricity, natural gas	
enbint(4,4:5)	Facility support: distillate, LPG	

Source: U.S. Energy Information Administration, Residential and Commercial Demand Modules

Cogeneration data - INDCOGEN.xml

This input file provides data associated with the cogeneration code and is read in the first year. The data are read in from an Excel file (indcogen.xml) as named ranges.

Table B-3. Cogeneration data

Input data	Description	Units
CogSizeKW(nsys)	Electricity capacity for steam systems—nsys is the number of systems and a parameter set to 8.	Real: kW
CapCostYearly	Total installed cost—endyr is set to 2050.	Real: 2015$/kW
CapFac(nsys)	Capacity Factor for the cogeneration system.	Real
CHeatRateYearly(2003:endyr,nsys)	Overall heat rate by year.	Real: Btu/kWh (HHV)
OverAllEffYearly(2003:endyr,nsys)	Overall efficiency by year.	Real
SteamSeg_Food(nload)	Percent of steam loads by load segment for Food – nload is the number of load segments and is a parameter set to 8.	Real
SteamSeg_Paper(nload)	Percent of steam loads by load segment for Paper.	Real
SteamSeg_Chem (nload)	Percent of steam loads by load segment for Chemicals.	Real
SteamSeg_Steel(nload)	Percent of steam loads by load segment for Steel.	Real
SteamSeg_Other(nload)	Percent of steam loads by load segment for Other Manufacturing.	Real
SteamSeg_Refin(nload)	Percent of steam loads by load segment for Refining.	Real
ThermalCap(nload)	Cogeneration thermal capacity.	Real: MMBtu/hour
Penetration(nload)	Yearly penetration fraction.	Real
AcceptFrac(13)	Fraction of firms willing to accept a payback period of N years or longer. Smaller plants.	Real
AcceptFrac2(13)	Same as AcceptFrac, but applies larger plants.	Real
CapCostMult(nsys)	Capital cost multiplier-used to implement policy options such as an investment tax credit.	Real
CapCostMultStart	Starting year in which CapCostMult goes into effect.	Integer
CapCostMultEnd	Ending year in which CapCostMult goes out of effect.	Integer
StandByFrac	Fraction of CogElecPrice representing standby charges.	Real

Higher heating value (HHV)—gross heating value—equal to the total heat obtained from combustion of a specified amount of fuel and its stoichiometrically correct amount of air, both being at 60°F when combustion starts, and after the combustion products are cooled. HHV assumes all the water component is in liquid state at the end of combustion.

Energy and production data file - ENPROD.txt

There are three separate sets of data in this file that are read in by the following three separate subroutines.

- o IRHEADER: Reads industry and region identifier numbers, base year values of output, physical to dollar output conversion factors, and base year steam demand. This input is required.
- o IRBSCBYP: Reads byproduct fuel information for the boiler, steam, and cogeneration component. These data consist of fuel identifier numbers and steam intensity values. This input is not required.
- o IRSTEPBYP: Reads byproduct data for process and assembly component. These data consist of fuel identifier numbers and heat intensity values. This input is not required. The step name is limited to eight characters since this name is placed in an eight character matrix for steps in the enprod.txt file. Otherwise, the limit is 24 characters. The step names from the prodflow.txt file are used.

The code that reads in the IRHEADER data calculates the ratio of physical output to 2014 (most recent Manufacturing Energy Consumption Survey data) value of shipments for pulp and paper, glass, cement, steel and aluminum industries. This constant ratio is applied to value of shipments for subsequent years.

Table B-4. Subroutine IRHEADER, IRBSCBYP and IRSTEPBYP input data

Input data	Description	Units
Subroutine IRHEADER		
Inddir	Industry ID.	Integer
Idval	Value indicating industrial output units of physical (1) or dollar value (2).	Integer
Phdrat	Factor used to convert industrial output from physical to dollar units.	Real
Dum	Reads in a dummy value that is not currently used.	Real
Stemcur	Steam demand from process and assembly and buildings.	Real
Subroutine IRBSCBYP		
Idum	Step number.	Integer
Ifx	This is the id number for the byproduct fuel that is stored in FSLOCBY(6) after being read in. The intermediate products and renewables from which the id number is selected are listed below.	Integer
(temp(J),J=1,2)	After being read in the data is stored in: BYSINT(IFSBYP) =TEMP(1) - Boiler Efficiency for byproduct fuel. Currently always 1.35. BYBSCSC(IFSBYP) =TEMP(2) - Conservation supply coefficient for byproduct fuel j. Values are all set to zero so not used.	Real
Subroutine IRSTEPBYP		
Idum	Step number.	Integer
Ifx	This is the id number for the byproduct fuel by process step that is stored in IFLOCBY(10,maxstep) after being read in. The intermediate products and renewables from which the id number is selected are listed below.	Integer
Temp(J),J=1,4	After being read in the data is stored in: BYPINT(3,5,maxstep) - vintaged byproduct unit energy consumption by region and process. TEMP(1) to vintage 1. TEMP(3) to vintage 2 and 3. BYPCSC(3,5,maxstep) - vintage byproduct efficiency coefficients by region and process. TEMP(2) to and TEMP(4) values are all set to zero so not used.	Real

THE INTERMEDIATE PRODUCTS QUANTITY ARRAY: QTYINTR(6,5)

1. STEAM (31)
2. COKE OVEN GAS (32)—currently used in enprod.txt
3. BLAST FURNACE GAS (33)—currently used in enprod.txt
4. OTHER BYPRODUCT GAS (34)
5. WASTE HEAT (35)—currently used in enprod.txt
6. COKE (36)

THE RENEWABLES QUANTITY ARRAY: QTYRENW(8,5)

1. HYDROPOWER (41)
2. BIOMASS-WOOD (42)—currently used in enprod.txt
3. BIOMASS-PULPING LIQUOR (43)—currently used in enprod.txt
4. GEOTHERMAL (44)
5. SOLAR (45)
6. PHOTOVOLTAIC (46)
7. WIND (47)
8. MUNICIPAL SOLID WASTE (48)

There is also the QTYMAIN(23,5) array that is the consumption of main fuels in census regions. The array QtyByInd is the sum of qtymain and qtyrenw into 18 reporting real categories by industry.

Industrial model control file - INDRUN.txt

These values generally do not change. Running the Energy Efficient case, the EETECH value is changed to 1. Unless otherwise indicated the value used in the table is the default value.

Table B-5. INDRUN.txt input variables

Input data	Description
ISUBTR	Write out the subroutine trace information (0=no, 1=yes). Set to 0.
INDMAX	The total number of industries in this run. Set to 21.
IWDBG	Should the debug file be written (0=no, 1=yes). Set to 0.
ISEDS	Benchmark to SEDS (0=no, 1=yes). Set to 1.
ICALIBRATE	Benchmark individual industry table to Table 6 US Total (1.0 = Default)
IPRICE	Should price sensitivities be done (0=no, 1=yes). Set to 0.
ELEC	ENTER PRICE SENSITIVITY FACTOR FOR ELECTRICITY (1.0=DEFAULT).
FGAS	ENTER PRICE SENSITIVITY FACTOR FOR FIRM NATURAL GAS (1.0=DEFAULT).
INTGAS	ENTER PRICE SENSITIVITY FACTOR FOR INTERUPTIBLE GAS (1.0=DEFAULT).
COAL	ENTER PRICE SENSITIVITY FACTOR FOR COAL (1.0=DEFAULT).
RESID	ENTER PRICE SENSITIVITY FACTOR FOR RESIDUAL OIL (1.0=DEFAULT).

Input data	Description
DIST	ENTER PRICE SENSITIVITY FACTOR FOR DISTILLATE OIL (1.0=DEFAULT).
LPG	ENTER PRICE SENSITIVITY FACTOR FOR LIQUID PETRO GAS (1.0=DEFAULT).
ITPC	Should tpc sensitivities be done (0=no, 1=yes). Set to 0.
TPC1	ENTER TPC SENSITIVITY FACTOR FOR OLD PLANTS (1.0=DEFAULT).
TPC2	ENTER TPC SENSITIVITY FACTOR FOR NEW PLANTS (1.0=DEFAULT).
FRZTECH	FROZEN TECHNOLOGY CASE (0=DEFAULT).
HITECH	HIGH TECHNOLOGY CASE (0=DEFAULT).
EETECH	ENERGY EFFICIENT CASE (0=DEFAULT)
IRETIRE	Should retirement rate model sensitivities be done (0=no, 1=yes). Set to 0.
RETRATE	ENTER RETIRMENT RATE SENSITIVITY FACTOR (1.0=DEFAULT).
LOOKAHEAD	Number of lookahead years for CHP and Motors (0=default). Set to 5.
carbshr(j)	Share of each industry's fossil consumption subject to carbon allowance costs. Currently all industry values are set to 1.0.

Boiler elasticities – ITLBSHR.txt

This file contains boiler elasticities and the latest MECS boiler, steam, and cogeneration (BSC) fuel totals. There are three separate data sets in the file.

Table B-6. ITBSHR.txt input variables

Input data	Description	Units
Parameters for logit boiler shares based on MECS		
Indint	Industry Code	Integer
Indrg	Region Code	Integer
Coeff(1)	Parameters for logit boiler shares. Currently set to (-2) for all industries and regions. Logic coefficients are stored in array TLBSHR(INDINT,INDRG,1).	Integer
Boiler Fuels from MECS		
j	The value for INDINT is set in code and read in as a dummy value from 7 (food) to 21. The non-manufacturing industries (1-6) are not included in the data.	Integer
j	The value for INDRG is set in code and read in as dummy value.	Integer
Temp(k),k=1,8	Latest MECS boiler/steam/cogen fuel in trillion Btu in the following order: resid, distillate, natural gas, LPG, coal, wood/biomass, other petroleum, and petcoke. Data is stored in array BSCIBYR(indint,indrg,Fuel) with the fuel index of:	Real: trillion Btu
	Coal(1)	
	Oil (2)—which includes sum of distillate, LPG, other petroleum, and petcoke.	
	Natural gas(3)	
	Wood/biomass(4)	
	Other cogeneration(5)—set to zero since no data.	
	MSW cogeneration(6)—set to zero since no data.	
	Resid(7)	
	Distillate(8)	
	LPG(9)	
	Other petroleum(10)	
	Petcoke(11)	

Table B-6. ITBSHR.txt input variables (cont.)

Input data	Description	Units
Size shares		
Indsize	Value is set in code from 1 to 6 corresponding to aggregated industries and some non-aggregated industries: non-manufacturing, food, paper, chemicals, metals, and other manufacturing.	Integer
Ifuel	Value is set in code from 1 to 4 corresponding to natural gas, coal, oil products, and biomass.	Integer
Sizeshrtemp(indsize,ifuel,1)	There are 24 input lines for the 6 industries and 4 fuels associated with each industry. Size share array by industry, fuel, and size group. There are two size groups with the two values summing to 1.0. The first column value is read to size group 1 (<= 10 MMBtu/hour) and the second column value is read to size group 2 (> 10 MMBtu/hour). Values are stored in sizeshr(inddir, jfuel, isize). Adjustments are made in code to apply the aggregated industries and fuel data to all of industries (21) and fuels (9) in the array sizeshr.	Integer

STEO history - INDSTEO.txt

This file contains the Short-Term Energy Outlook data with the last available history data and national projections for the next two years.

Table B-7. INDSTEO input data

Input Data	Description	Units
Iyear	The last four historical years.	Integer
SF	Counting integer for fuel inputs. Fuel inputs are labeled in the indsteo.txt file.	Integer
STEOQ(IYEAR,SF)	STEO history and projections by year.	Real

Production flows - PRODFLOW.txt

The file has three sections for each industry: step definitions, retirement rates, and prodflow rates for each step. Reporting groups are also read in for some industries with process steps.

The MECSBASE subroutine imports production throughput coefficients, process step retirement rates, and other process step flow information from the file PRODFLOW.TXT. Imported process step flow data for each process step include process step number, number of links, the process steps linked to the current step, physical throughput to each process step, retirement rate, and process step name.

Data lines starting with an asterisk (*) are not read in. Reporting groups modify the output to the reports indusa.xml and indreg(1-4).xml.

Table B-8. PRODFLOW steps and reporting groups

Input data	Description	Units
Number of steps and reporting groups		
Inpind	Industry code	Integer
Inpreg	Region	Integer
Nsteps	Number of process steps	Integer
Ngrps	Number of reporting groups. Typically set to 0. When set to another value then there is an additional input defining the reporting groups.	
Step definitions		
Inpind	Industry code	Integer
Inpreg	Region	Integer
Inpstp	Process step	Integer
Duma	Dummy data and comment not used.	Character*20
Dumc	Dummy data and comment not used.	Character*15
ntmax(inpstp)	Maximum number of links for the process step.	Integer
IPASTP(inpstp,IDOWN)	Stores 0 or 1 values indicating process links. The values read are the process steps with links. These values are transformed when read in to 0 or 1 values stored in the array IPASTP.	Integer
Reporting group definitions (only included for an industry if ngrps is greater than 0)		
Inpind	Industry code.	Integer
Inpreg	Region	Integer
Inpg	Reporting group – 1 to ngrps.	Integer
RptGrpNames(inpg)	Name of the reporting group.	Character*24
NumRptGrpSteps(inpg)	Number of steps in the reporting group.	Integer
RptGrpSteps(NumRptGrps + 1,is)	Process steps for the reporting group.	Integer
RptGrpNames(NumRptGrps+1,is)	Reporting group step labels.	Character*24
Retirement rates		
Inpind	Industry code	Integer
Inpreg	Region	Integer
Inpstp	Process step	Integer
Indstepname(inpstp)	Step name.	Character*24
Dumc	Dummy comment that is not used.	Character*15
PRODRETR(inpstp)	Retirement rate by process step.	Real

Table B-8. PRODFLOW steps and reporting groups (cont.)

Input data	Description	Units
Production flow rates		
Inpind	Industry code	Integer
Inpreg	Region	Integer
Ivint	Vintage that is read in with the production flow data only. Only Vintage 1 (old) and 3 (mid) data are provided.	Integer
Inpstp	Process step	Integer
Dumc	Dummy comment that is not used.	Character*15
prodflow(min(ivint,2),inpstp, idown)	Dimension 2 for Production volume to be read in for the old and middle vintage. Vintage 1 is placed in index 1 and vintage 3 is placed in index 2. The production flow is then read in for each step and link.	Real

Industrial motor inputs - INDMOTOR.xml

Table B-9. Data inputs for indmotor.xml

Input data	Description	Units
MotSysLife(NI,motorsizes)	Motor system efficiency program life: NI industries, 7 motor sizes.	Real
PumpAppPct(NI,motorsizes)	System efficiency applicability, % pumps: NI industries, 7 motor sizes.	Real
FanAppPct(NI,motorsizes)	System efficiency applicability, % fans: NI industries, 7 motor sizes.	Real
CompAppPct(NI,motorsizes)	System efficiency applicability, % compressors: NI industries, 7 motor sizes.	Real
PumpSavPct	System efficiency savings fraction, pumps: NI industries, 7 motor sizes	Real
FanSavPct	System efficiency savings fraction, fans: NI industries, 7 motor sizes	Real
CompSavPct	System efficiency savings fraction, compressors: NI industries, 7 motor sizes	Real
NI	Number of industries programmed for motors – parameter value of 10.	Integer
Motorsizes	There are seven motor sizes in the data.	

Existing and planned cogeneration capacity - EXSTCAP.txt and PLANCAP.txt

The following describes the units in the input file. These values are then stored with unit conversions as shown in the table below.

- o capacity (cogcap): Total summer capacity in kW. Note however that the reported capacity for each generator is only associated with its primary fuel, so any additional fuels assigned to the generator will have a corresponding capacity of zero. For example, if a generator primarily uses steam from coal, but also burns some natural gas or petroleum liquids in the boiler associated with the generator, this factor will be reflected with positive generation being added to both the coal and natural gas or petroleum liquids aggregates, but only the coal will reflect a positive addition to their capacity aggregates. This fact will cause a slight skew in variable capacity factor
- o generation (coggen): annual generation in kilowatthours (kWh)
- o elec fuel use (cogelf): total annual consumption in million Btu (MMBtu)
- o thermal (cogthr): useful thermal output in MMBtu
- o cap fact (read in, but not stored): total annual generation (kWh) / (capacity(kW) * hours in a year)
- o incr. heatrt (read in, but not stored): [total annual consumption in MMBtu/total annual generation in kilowatthours (kWh)]*1000000, which ultimately brings the units to Btu/kWh
- o grid share (coggrd): industry/census weighted average of (total_generation(kWh)-facility_use(kWh))/total_generation(KWh). Note that this share is not fuel-specific, so all fuels in each industry/census group will have the same grid share value

Table B-10. EXSTCAP.txt & PLANCAP.txt input data

Input data	Description	Units (Read in)
Iyear	Year	Integer
Adum	Dummy input	Character*25
Ind	Industry	Integer
ir	Census division	Integer
Adum	Dummy input	Character*25
Ifuel	Fuel index	Integer
cogcap(ir,iyear,ind,ifuel)/1000	Capacity	kW
coggen(ir,iyear,ind,ifuel)/1000000	Generation	kWh
cogelf(ir,iyear,ind,ifuel)/1000000	Electricity fuel use	MMBtu
cogthr(ir,iyear,ind,ifuel)/1000000	Useful thermal output	MMBtu
Read in, but not stored	Capacity factor	Real
Read in, but not stored	Incremental heat rate	Real: Btu/kWh
coggrd(ir,iyear,ind,ifuel)/1000000	Grid share	Real

The data source for PLANCAP.txt is also EIA 860 survey. This file is manually edited by removing the planned build for Oil n Gas Extrk because this CHP is covered under another NEMS module. The data that is read in has the same format as for EXSTCAP.txt except is stored in the array cogadd.

Process and Assembly step input (end-use industries only): itech.txt
The itech file contains unit energy consumption for the end-use industries to be used for energy consumption in process and

Table B-11. ITECH.txt inputs UECs and TPCs.

Input data	Description
i_ind	Industry number
i_ir	Region number
i_stp	Step number
Duma	Dummy input
i_ifx	Fuel code
Duma	Dummy input
einter(1,i_ifx,i_stp)	UEC base year, original vintage
minpint(1,i_ifx,i_stp)	UEC 2050, original vintage
bcsc(1,i_ifx,i_stp)	TPC, original vintage
einter(3,i_ifx,i_stp)	UEC base year, new vintage
minpint(3,i_ifx,i_stp)	UEC 2050, new vintage
Bcsc(3,i_ifx,i_stp)	TPC, new vintage

Cost, Performance, and Physical Input Data for Five Process Flow Industries in IRONSTLX.xlsx

The first table has variables that are related to input data from ironstlx.xlsx for process flow models: cement and lime, aluminum, glass, iron and steel, and paper. Each industry is on its own labeled tab in the spreadsheet. Each tab in the input file has ranges that are defined and read into the listed variables from the subroutine IS_GETDATA. Many of the same array variables are used in the process flow industries. The following five tables list inputs for each industry.

Table B-12. Steel input data in IRONSTLX.xlsx

Input data	Description	Type
Inumreg	Number of regions set to four census regions.	Integer

Input data	Description	Type
ICURIYR	Current base year index of 21 that represents the base year of 2014.	Integer
B_SHR	Initial and final shares of conventional boilers.	Real
B_T_Final(N_Boil_Tech)	Final shares of each boiler technology and final year.	Real
B_T_Start(N_Boil_Tech)	Initial shares of each boiler technology and initial year.	Real
B_T_YEAR(2)	Years for B_T_Start and B_T_Final.	Real
B_YEAR(2)	Initial and final years to calculate shares of conventional boilers.	Real
Base_BOF(inumreg)	Regional base year (2014) value for BOF element.	Real
Base_Coke(inumreg)	Regional base year (2014) value of coke PRODFLOW element.	Real
Base_Cold(inumreg)	Regional cold-rolled share in base year (2014).	Real
Base_EAF(inumreg)	Regional base year (2014) value for EAF Element.	Real
billbar(4)	Hot roll energy use for billets products bars fuels natural gas, HFO, and electricity. Also, CO2 emissions (T/KT).	Real
billrod(4)	Hot roll energy use for billets products rods fuels natural gas, HFO, and electricity. Also, CO2 emissions (tons/kT).	Real
billshape(4)	Hot roll energy use for billets products light structure. shapes fuels natural gas, HFO, and electricity. Also, CO2 emissions (tons/kT).	Real
bloomstruct(4)	Hot roll energy use for blooms products heavy structure. shapes fuels natural gas, HFO, and electricity. Also, CO2 emissions (tons/kT).	Real
bloomtubes(4)	Hot roll energy use for blooms products tubes fuels natural gas, HFO, and electricity. Also, CO2 emissions (tons/kT).	Real
BOIL_Intensity(5,N_Boil_Tech)	Fuel and CO2 intensity factors for conventional boilers.	Real
C_T_Final(N_CHP_Tech)	Final shares of each CHP technology and final year.	Real
C_T_Start(N_CHP_Tech)	Initial shares of each CHP technology and initial year.	Real
C_T_YEAR(2)	Years for C_T_Start and C_T_Final.	Real
cc_ngas(4)	Continuous casting natural gas, HFO, elec, CO2.	Real
cc_oil(4)	Continuous casting natural gas, HFO, elec, CO2.	Real
cc_shrfinal(2)	Continuous casting ending shares and year to forecast future shares.	Real
cc_shrstart(2)	Continuous casting starting shares and year to forecast future shares.	Real

Input data	Description	Type
CHP_Intensity(5,N_CHP_Tech)	Fuel and CO2 Intensity factors for CHP systems.	Real
CO2_Intensity(6,2)	Emissions of CO2, by sub-process (ton/kT of production).	Real
DRI_Tot_Phase1(inumreg)	Total production of DRI in initial year (currently tentatively, 2015).	Real
DRI_Tot_Phase2(inumreg)	Total production of DRI in later year (currently tentatively, 2020).	Real
formshares(3)	Hot roll shares for blooms, billets and slabs.	Real
HFO_Share	Share of cold-rolled steel production using HFO technologies (%).	Real
Intensity(3,6)	Energy intensity by fuels natural gas, electricity, HFO, and sub-process (MMBtu/kT).	Real
is_add_tech_share(inumind,maxstep, MAXTECH)	Share for each added technology for IS 1, 3, to 7.	Real
is_alpha(inumind,maxstep, MAXTECH)	Alternative-Specific constant for IS 1, 3 to 7.	Real
is_alpha_decay(inumind,2)	Alpha decay factor that reduces alternative specific constants.	Real
is_Alpha_Furnace(inumreg)	Sensitivity parameter uniform across regions/fuels for simplicity.	Real
is_av_OM(inumind,maxstep, MAXTECH)	Technology O&M Cost ($/1000 Tonnes) for IS 1,3, to 7.	Real
is_base_tech_share(inumind,maxstep,MAXTECH)	Share for each baseline technology for IS 1, 3 to 7.	Real
is_baselifecr(inumind)	Baseline capacity lifetime.	Integer
is_BldCHPShr	Building CHP share.	Real
is_calib(inumind)	Technology survival curve calibration constant (user-specified).	Integer
is_capcost(inumind,maxstep, MAXTECH)	Technology Capital Cost ($/1000 Tonnes) for IS 1, 3, to 7.	Real
is_CapFacAvg(4)	Capacity Factor Weighted average.	Real
IS_cenergy_use(7)	Coke Energy Use (MMBtu/kt) adjusted after read in with is_steam_adj.	Real
is_co2penalty(inumind,ICURIYR:MNUMYR)	CO2 penalty starting with 2014 and to the end of the projection period. Applied to all process flow industries to include pulp and paper.	Real
IS_CProcess(4)	Coke Process Output factors; breeze, cog, tars, light oils.	Real
IS_emiss(inumind,maxstep, MAXTECH)	Technology CO2 Emissions (T/kT) for IS 1, 3 to 7.	Real
is_FISYR(inumind)	First calculated year.	Integer
IS_fuel_use(inumind,maxstep, IS_MAXFUEL,MAXTECH)	Fuel Intensity: 1=elec, 2=ng, 3=hfo, and 4=coal, (MMBTU/kt) for 1,3, to 7.	Real

Input data	Description	Type
is_ibyrvals(5,5)	Baseyear model results by region and fuel.	Real
is_lifetime(inumind)	Technology lifetime in years.	Real
is_logit_coeff(inumind,5,maxstep)	Logit Coefficients for (1) Fixed Cost, (2) Fuel Cost, and (3) Emissions.	Real
is_Max_Delta(inumreg)	Constraint on annual changes to EAF/BOF shares.	Real
is_mecsbench(5)	MECS benchmark factors for elec, ng, resid, steam coal, and met coal.	Real
IS_nfuel_use(inumind,maxstep,2, MAXTECH)	Non Fuel Intensity: 1=oxygen, and 2=steam (MMBTU/kt) for 1, 3, to 7. Adjusted after read in with is_steam_adj.	Real
is_numfuel(inumind,maxstep)	Number of fuels in each step.	Integer
is_numtech(inumind,maxstep)	Number of technologies in each step.	Integer
Is_production(inumind,maxstep)	Historical Step production (1000 tonnes), (aka PRODCUR).	Real
is_steam_adj	SIMS Steam adjustment factor.	Real
is_wacc(inumind)	Weighted Average Cost of Capital (WACC).	Real
iscr_shares(2:6)	Shares of cold-rolled steel by sub process (Percent).	Real
NG_Share	Share of Cold-Rolled Steel production using NG Technologies (Percent).	Real
obsoleteyr(inumind,maxstep, MAXTECH)	Technology obsolescence year for IS 1, 3, to 7.	Real
Phase1_YR(inumreg)	Initial year of DRI capacity addition.	Integer
Phase2_YR(inumreg)	Final year of DRI capacity addition.	Integer
shrfinal(12)	Hot roll ending shares and year to forecast future shares.	Real
shrstart(12)	Hot roll starting shares and year to forecast future shares.	Real
slabskin(2)	Hot Roll electricity use for the slab product technologies Skin_Pass and Pickling.	Real
slabtech1(2)	Hot Roll electricity use for the slab product technology 1 for roughing and finishing technologies.	Real
slabtech2(2)	Hot Roll electricity use for the slab product technology 2 for roughing and finishing technologies.	Real

Table B-13. Paper input data in IRONSTLX.xlsx

Input data	Description	Type
BldCHPShr	Building CHP share.	Real

Input data	Description	Type
CapFacAvg(2,4)	Capacity factor weighted average.	Real
El_Adj	Electricity bench factor; used to benchmark fuel use before model runs to ultimately bench to MECS.	Real
hog_heat	Hog net heat content.	Real
hog_pulp	Tonnes wood/tonnes pulp.	Real
hog_waste	Percentage of waste to hog fuel.	Real
ibyr_survcap(inumind,maxstep)	Base year surviving capacity.	Real
is_add_tech_share(inumind,maxstep, MAXTECH)	Share for each added technology.	Real
is_alpha(inumind,maxstep,MAXTECH)	Alternative-Specific Constant.	Real
is_alpha_decay(inumind,2)	Alpha decay factor (reduces alternative specific constants).	Real
is_av_OM(8:13,maxstep,MAXTECH)	Technology O&M Cost ($/1000 Tonnes).	Real
is_base_tech_share(inumind, maxstep, MAXTECH)	Share for each baseline technology.	Real
is_baselifecr(inumind)	Baseline capacity lifetime.	Integer
is_calib(inumind)	Technology Survival Curve Calibration Constant (user-specified).	Integer
is_capcost(8:13,maxstep,MAXTECH)	Technology Capital Cost ($/1000 Tonnes).	Real
IS_emiss(inumind,maxstep, MAXTECH)	Technology CO2 Emissions (T/kT).	Real
is_FISYR(inumind)	First calculated year.	Integer
IS_fuel_use(inumind,maxstep, IS_MAXFUEL,MAXTECH)	Fuel Intensity for 1=elec, 2=ng, 3=hfo, and 4=coal, in (MMBTU/kt).	Real
is_lifetime(inumind)	Technology Lifetime (years).	Real
is_logit_coeff(inumind,5,maxstep)	Logit Coefficients for (1) Fixed Cost, (2) Fuel Cost, (3) Emissions.	Real
IS_nfuel_use(inumind,maxstep,2, MAXTECH)	Non Fuel Intensity for 1=oxygen, and 2=steam (MMBTU/kt).	Real
is_numfuel(inumind,maxstep)	Number of fuels in each step.	Integer
is_numtech(inumind,maxstep)	Number of technologies in each step.	Integer
is_production(inumind,maxstep)	Historical Step production (1000 tonnes), (aka PRODCUR).	Real
is_wacc(inumind)	Weighted Average Cost of Capital (WACC).	Real
Mech_Share(17:MNUMYR)	Allocation share between Mechanical and Thermo-mechanical Pulping Technologies.	Real

Input data	Description	Type
obsoleteyr(inumind,maxstep, MAXTECH)	Technology obsolescence year.	Real
Paper_Share(5,17:MNUMYR)	Allocation shares for paper production (five paper types).	Real
pp_BioBoilEff	IDM boiler efficiency (biomass).	Real
pp_blkliq(maxstep,MAXTECH)	Paper black liquor.	Real
pp_chip	Electric fuel use for wood preparation chipping.	Real
pp_hfoshr(4)	Share out HFO: resid, petcoke, distillate, and other.	Real
pp_hogfuel	Paper hog fuel.	Real
pp_ibyrvals(5,7)	Base year model results by regions and fuel.	Real
pp_mecsbench(7)	MECS benchmark factors.	Real
PP_ProxyDat(17:MNUMYR)	Data from the macroeconomic model that will be directly passed to the IDM (2006–2050).	Real
pp_steam(maxstep,MAXTECH)	Paper steam (units/kT).	Real
PP_STM_RYCL	Percent steam that is recycled (pulp and paper).	Real
pp_stmfuel_bl(9,5)	Boiler fuel use for paper steam.	Real
pp_stmfuel_chp(9,5)	CHP fuel use for paper steam.	Real
ppst_shrfinal(17,2)	Final shares for paper steam.	Real
ppst_shrstart(17,2)	Starting shares for paper steam.	Real

Source: Consolidated Impacts Modeling System and Industrial Demand Module

Table B-14. Cement and lime input variables in ironstlx.xlsx

Variable	Subroutine(s)	Explanation	Last update
Cm_add	kiln_capacity,	Proportion of finish grinding tonnes composed of other additives	AEO2012
alpha_burner	cm_burner	Technology coefficients used in calculating surviving capacity; six technologies available	AEO2012
alpha_rg	cm_raw_grind	Technology coefficients used in calculating surviving capacity; two dimensions	AEO2012

Variable	Subroutine(s)	Explanation	Last update
Cm_Baselifecr`	cm_burnercm_burner, kiln_allocation, kiln_capacity , cm_raw_grindcm_raw_grind Tech_Step	Lifespan of base capacity (years)	AEO2012
Cm_BaseLifeDry	kiln_capacity	Years until total retirement of existing stock of Dry Process capacity	AEO2012
Cm_BaseLifeWet	kiln_capacity	Years until total retirement of existing stock of Wet Process capacity	AEO2012
burner_coeff	cm_burner	Used in calculation for burner fuel use; indexed by technology	AEO2012
calib_coeff	cm_burner, cm_raw_grind	Calibration coefficients for burner fixed cost, fuel cost, emissions, and particulate emissions	AEO2012
Calibration	cm_burner, kiln_capacity, cm_raw_grind Tech_Step	Calibration coefficient used in calculating surviving capacity	AEO2012
cm_capshr(1:2)	kiln_capacity	Shares of baseline kiln capacity accommodated by Wet and Dry Process kilns	AEO2012
demand_IBYR	Tech_Step	Historical demand, model base year (2008)	AEO2012
demand_IBYR2	Tech_Step	Historical demand 2009	AEO2012
cm_elec_coeff	kiln_allocation	Coefficient used to calculate cement kiln energy consumed based on clinker output and other variables; energy use increases when coefficient value increased	AEO2012
cm_flyash	Tech_Step	Proportion of finished cement that is composed of power plant fly ash	AEO2012
cm_heatcoef	kiln_allocation	Coefficient used to calculate heat requirement based on clinker production and other variables; heat requirement increases when coefficient value increased	AEO2012

Variable	Subroutine(s)	Explanation	Last update
Cm_heatd_coeff	cm_burner	Coefficient (GJ/tonne of clinker) used to calculate wet process heat requirement ; from USGS Minerals Yearbook	AEO2012
cm_import_clink	kiln_capacity , Tech_Step	Proportion of finish grinding tonnes composed of imported clinker	AEO2012
Cm_lifetime	cm_burner, kiln_capacity, k, cm_raw_grind Tech_Step	Lifespan of new capacity (years)	AEO2012
C_mass_loss	, cm_raw_grind Tech_Step	Amount of kiln output in the wet cement process (> 1 ton) to get one ton of grinding output	AEO2012
shipments_IBYR	Tech_Step	Cement shipments_IBYR in kilotonnes 2014	AEO2012
shipments_IBYR2	Tech_Step	Shipments_IBYR in kilotonnes 2015	AEO2012
IS_base_tech_share	cm_burner, finish_grind_alloc, finish_grind_alloc, kiln_allocation, cm_raw_grindc Tech_Step	Technology share values in base year	AEO2012
cm_wacc	cm_burner, , kiln_allocation, cm_raw_grind, Tech_Step	Weighted average cost of capital; user input	AEO2012
Cm_wet_coeff	cm_burner, cm_raw_grind	Allocation by burner type (wet process) from CIMS data	AEO2012

Source: Consolidated Impacts Modeling System and Industrial Demand Module

Table B-15. Aluminum input variables ironstlx.xlsx

Variable	Subroutine(s)	Explanation	Last update
AL_ALPHA_DECAY	TECH_STEP	Data for runs (REF, HITECH, FRZTECH, EETECH). Alpha decay factor (reduces alternative specific constants).	AEO2018
AL_MASS_LOSS	TECH_STEP	Mass loss converting alumina to aluminum.	AEO2018
al_mecsbench	AL_BENCHMECS	MECS benchmark factors: Electricity, Natural Gas, Residual.	AEO2018
AL_NON_MET	TECH_STEP	Non-Metallic use of alumina.	AEO2018

Variable	Subroutine(s)	Explanation	Last update
al_pf_fuel	AL_prod_form	Total Trillion Btu per kTonne used for product formation fuel use.	AEO2018
alumina_percent	TECH_STEP	Alumina Imports (Percent of Domestic Use).	AEO2018
AnodeRatio	AL_anode_prd	Tonnes of Anode Per Ton of AL.	AEO2018
ibyr_survcap	Step_Capacity	Base year surviving capacity.	AEO2018
is_alpha	TECH_STEP	Alternative-Specific constant for IS 1, 3 to 7.	AEO2018
is_add_tech_share	TECH_STEP	Share for each added technology.	AEO2018
IS_BASELIFECR	TECH_STEP	Baseline capacity lifetime.	AEO2018
IS_BASE_TECH_SHARE	AL_anode_prd TECH_STEP	Share for each baseline technology.	AEO2018
IS_AV_OM	TECH_STEP	Technology O&M Cost ($/1000 Tonnes).	AEO2018
IS_CALIB	TECH_STEP	Technology Survival Curve Calibration Constant (user-specified).	AEO2018
IS_CAPCOST	TECH_STEP	Technology Capital Cost ($/1000 Tonnes).	AEO2018
IS_CO2PENALTY	TECH_STEP	CO2 penalty starting with 20104 and to the end of the projection period. Applied to all process flow industries to include pulp and paper.	AEO2018
is_ecalib	TECH_STEP	Electricity calibration.	AEO2018
is_delta	TECH_STEP	Potential efficiency improvements = % difference between best practice and current practice.	AEO2018
IS_EMISS	TECH_STEP	Technology CO2 emissions (tons/kilotonne).	AEO2018
IS_FISYR	TECH_STEP	First calculated year.	AEO2018
IS_FUEL_USE	AL_anode_prd TECH_STEP	Fuel Intensity: 1=electricity, 2=natural gas, 3=HFO, and 4=coal, (MMBtu/kilotonne) for 1, 3 to 7.	AEO2018
IS_LIFETIME	TECH_STEP	Technology lifetime (years).	AEO2018
IS_LOGIT_COEFF	TECH_STEP	Logit coefficients for (1) fixed cost, (2) fuel cost, and (3) emissions.	AEO2018
IS_NFUEL_USE	TECH_STEP	Non-fuel intensity for 1=oxygen, and 2=steam (MMBtu/kilotonne).	AEO2018

Variable	Subroutine(s)	Explanation	Last update
IS_NUMFUEL	TECH_STEP	Number of fuels in each step.	AEO2018
IS_NUMTECH	AL_anode_prd TECH_STEP TECHSHR_RPT	Number of technologies in each step.	AEO2018
is_production	AL_prod_form TECH_STEP	Historical production (kilotonnes), (aka PRODCUR).	AEO2018
IS_WACC	TECH_STEP	Weighted average cost of capital (WACC).	AEO2018
Obsoleteyr	TECH_STEP	Technology obsolescence year.	AEO2018

Source: Consolidated Impacts Modeling System and Industrial Demand Module

Table B-16. Glass input variables ironstlx.xlsx

Variable	Subroutine(s)	Industry	Explanation	Last update
GL_ALPHA_DECAY	TECH_STEP	Glass	Alpha decay factor (reduces alternative specific constants).	AEO2018
GL_CRYO	Glass_Industry	Glass	Related to flat technologies associated with oxy fuel sheet GL_OXY(1,:).	AEO2018
GL_hist_ship	GL_Shipping	Glass	Historical shipping shares by glass type for six historical years.	AEO2018
GL_MECS	CALPATOT	Glass	MECS benchmark factors (natural gas, electricity)	AEO2018
GL_OXY	Glass_Industry GL_OxyFuel TECH_STEP	Glass	Oxy impact on fuel consumption. Oxygen requirements for typical glass-producing plants in tonnes O2/tonne glass. Oxy share factors: 1-base 2-max 3-trigger 4-k	AEO2018
IS_ADD_TECH_SHARE	TECH_STEP	Glass	Share for each added technology.	AEO2018
IS_ALPHA	TECH_STEP	Glass	Alternative-specific constant for IS1, 3 to 7.	AEO2018
IS_AV_OM	TECH_STEP	Glass	Technology O&M Cost ($/kilotonne).	AEO2018
IS_BASELIFECR	TECH_STEP	Glass	Baseline capacity lifetime.	AEO2018
IS_BASE_TECH_SHARE	TECH_STEP	Glass	Share for each baseline technology.	AEO2018

Variable	Subroutine(s)	Industry	Explanation	Last update
IS_CALIB	TECH_STEP	Glass	Technology survival curve calibration constant (user-specified).	AEO2018
IS_CAPCOST	TECH_STEP	Glass	Technology capital cost ($/kilotonne).	AEO2018
IS_EMISS	TECH_STEP	Glass	Technology CO2 Emissions (tons/kilotonne).	AEO2018
IS_FISYR	TECH_STEP	Glass	First calculated year.	AEO2018
IS_FUEL_USE	TECH_STEP GL_OxyFuel	Glass	Fuel Intensity: 1=electricity, 2=natural gas, 3=HFO, and 4=coal; (MMBtu/kilotonne) for 1, 3 to 7.	AEO2018
IS_LIFETIME	TECH_STEP	Glass	Technology lifetime (years).	AEO2018
IS_LOGIT_COEFF	TECH_STEP	Glass	Logit Coefficients for (1) fixed cost, (2) fuel cost, and (3) emissions.	AEO2018
IS_NUMFUEL	TECH_STEP	Glass	Number of fuels in each step.	AEO2018
IS_NUMTECH	GL_OxyFuel, TECH_STEP	Glass	Number of technologies in each step.	AEO2018
is_production	CALPATOT, TECH_STEP	Glass	Historical step production (kilotonnes), (aka PRODCUR).	AEO2018
IS_WACC	TECH_STEP	Glass	Weighted average cost of capital (WACC).	AEO2018
Obsoleteyr	TECH_STEP	Glass	Technology obsolescence year.	AEO2018

Source: Consolidated Impacts Modeling System and Industrial Demand Module

Benchmark Factors Input Data – IBFACTRI.csv

Benchmark factors by fuel and renewable energy sources are read in from ibfactri.csv by the subroutine IRSTEO for each of the four census regions over the projection period years from 2014 to 2050. This file is used in the benchmark side case. In some cases there are no factors associated with fuels and renewables in a particular region. Some fuels also do not have any factors such as NA (not a fuel at present), lease and plant, still gas, and kerosene. Some renewables do not have any factors such as geothermal, solar, photovoltaic, and wind.

Table B-17. IBFACTRI.csv benchmark factors input data

Input data	Description	Units
HISTBF(ICURIYR:LASTYR,IFUEL,ICR).	Historical benchmark fuel factors read in from ibfactri.csv.	Real
IFUEL	Fuels index: Electricity, NA, NG CORE, NG NONCORE, NG FEEDSTOCK, LEASE AND PLANT, STEAM COAL, MET COAL , NET COKE IMPORT, RESID, DISTILLATE, LPG HP, LPG FEEDSTOCK, MOGAS, STILL GAS, PET COKE, ASPHALT, LUBES & WAXES, PET CHEM FEED, KEROSENE, OTHER PETRO FEED, and OTHER PETRO.	Integer
RHISTBF(ICURIYR:LASTYR, IFUEL,ICR)	Benchmark renewable factors read in from ibfactri.csv	Real
IFUEL	Renewable energy sources from 1 to 8: HYDROPOWER, BIOMASS-WOOD, BIOMASS-PULPING, GEOTHERMAL, SOLAR, PHOTOVOLTAIC, WIND, and MSW.	Integer
ICURIYR	Current base year index of 21 that is year 2014.	Integer
LASTYR	Last projection year index of 61 that is year 2050.	Integer
ICR	The four census regions of 1 to 4.	Integer

Feedstock History Input Data – feedstkaer.csv

This file contains industrial (non-refinery) feedstock consumption data for the entire United States for the years 1990 to 2005. The feedstock data are for natural gas, ethane, propane, propylene, normal butane, isobutane, natural gasoline, and naphtha. The data are based on EIA survey data of natural gas, hydrocarbon gas liquids, and naphtha. Analyst judgement is used to split out olefins from alkanes before 1993.

The subroutine READ_FEEDSTOCK_AER reads the data from feedstkaer.csv and populates the variables shown in Table B-18.

Table B-18. feedstkaer.csv feedstock history input data

Input data	Description	Units
aerngfeedhistory	Natural gas feedstock	Real: trillion Btu
aerlpgfeedhistory	Total hydrocarbon gas liquid feedstock (sum of ethane, propane, propylene, normal butane, isobutane, and natural gasoline)	Real: trillion Btu
aerethfeedhistory	Ethane feedstock	Real: trillion Btu
aerpropanefeedhistory	Propane feedstock	Real: trillion Btu
aernormbutanefeedhistory	Normal butane feedstock	Real: trillion Btu
aerisobutanefeedhistory	Isobutane feedstock	Real: trillion Btu
aerpropylenefeedhistory	Propylene feedstock	Real: trillion Btu
aernatgasolinefeedhistory	Natural gasoline feedstock	Real: trillion Btu
aernaphfeedhistory	Naphtha feedstock	Real: trillion Btu

Feedstock History and Projections – feedstock.csv

This file contains historical (non-refinery) industrial feedstock consumption data for the entire United States from 2006 through the last SEDS year, then projections through the year after the last STEO year. The feedstock data are for natural gas, ethane, propane, propylene, normal butane, isobutane, natural gasoline, and naphtha. The data are based on EIA survey data of natural gas, hydrocarbon gas liquids, and naphtha. The projected feedstock consumption is based on a combination of research into planned petrochemical projects, preliminary survey data, and analyst judgment.

The subroutine READ_FEEDSTOCK reads the data from feedstock.csv and populates the variables shown in Table B-19.

Table B-19. Feedstock.csv feedstock history and projections input data

Input data	Description	Units
MAX_YEARS	Year index going from 2006 (1) to the year after the last STEO year	Integer
Feedngtotal	Natural gas feedstock	Real: trillion Btu
Feedlpgtotal	Total hydrocarbon gas liquid feedstock (sum of ethane, propane, propylene, normal butane, isobutane, and natural gasoline)	Real: trillion Btu
Feedethtotal	Ethane feedstock	Real: trillion Btu
Feedpropanetotal	Propane feedstock	Real: trillion Btu
Feednormbutanetotal	Normal butane feedstock	Real: trillion Btu
Feedisobutanetotal	Isobutane feedstock	Real: trillion Btu
Feedpropylenetotal	Propylene feedstock	Real: trillion Btu
Feednatgasolinetotal	Natural gasoline feedstock	Real: trillion Btu
Feednaphtotal	Naphtha feedstock	Real: trillion Btu

Ethane Feedstock Census Region Split – ethanereg.csv

This file contains the fraction of total U.S. ethane feedstock consumption in each census region, by year. The data go from 1990 through the fourth year after the last STEO year. The regional split is based on EIA's internally-maintained database on petrochemical cracking capacity at the plant level. No ethane feedstock is consumed in regions other than Middle Atlantic, East North Central, West North Central, East South Central, and West South Central.

The subroutine READ_ETH_FRAC populates the variable EthaneDivFrac(IYR, ICD) with the data from this file, where IYR is the index year (with 1990=1) and ICD is the census division.

Propane Feedstock Census Region Split – propanereg.csv

This file contains the fraction of total U.S. propane feedstock consumption in each census region, by year. The data go from 1990 through the fourth year after the last STEO year. The regional split is based

on EIA's internally-maintained database on petrochemical cracking capacity at the plant level and reported product supplied numbers in EIA's *Petroleum Supply Annual*. No propane feedstock is consumed in regions other than East North Central, West North Central, East South Central, and West South Central.

The subroutine READ_PROP_FRAC populates the variable PropaneDivFrac(IYR, ICD) with the data from this file, where IYR is the index year (with 1990=1) and ICD is the census division.

Industrial demand module hardcoded data

There are currently hardcoded data in the Industrial Demand Module that will need to be changed from time to time.

Table B-20. Hardcoded variables in the IDM

Variable	Subroutine(s)	Industry	Explanation	Last update
AG_Bldg_Wt	AGTPC	Agriculture	Shares of energy consumption for each major fuel for each major use: heating, lighting, and building shell	AEO2013
Alefficiency	CALPROD	Aluminum	Electrical efficiency data for aluminum	AEO2013
Alintercept	CALPROD	Aluminum	Intercept term for regression of primary aluminum ratio to total aluminum production on electricity prices	AEO2013
Alslope	CALPROD	Aluminum	Electricity price term from regression of primary aluminum ratio to total aluminum production on electricity prices	AEO2013
Alslopelag	CALPROD	Aluminum	Lagged electricity price term from regression of primary aluminum ratio to total aluminum production on electricity prices	AEO2013
Avebeff	CALBSC	All except iron and steel, paper, and aluminum	Average boiler efficiency for boilers by type of fuel (for example, natural gas, petroleum coke)	AEO2012
Beff	CALSTOT	All except iron and steel, paper, and aluminum	Average boiler efficiency for boilers by type of fuel. Should be identical to beff	AEO2012
Biofactor	CALGEN	All except iron and steel, paper, and aluminum	Incremental biomass capacity available for CHP	AEO2012
Biocapfac	CALGEN	All except iron and steel, paper, and aluminum	Capacity factor of CHP biomass capacity	AEO2012
Bypbeff	CALGEN	All except iron & steel and paper	Boiler efficiency by fuel for 6 fuels	AEO2014

Variable	Subroutine(s)	Industry	Explanation	Last update
Bypcsc	CALBYPROD	All except iron & steel and paper	UECs (bypcsc array) are assigned for the rate of byproduct energy produced.	AEO2012
clinkFac	N/A	Cement	Converts tons of clinker to metric tons of carbon	AEO2012
Coggrdnew	CALGEN	All except iron & steel and paper	Assumed grid share for new capacity additions; initialized from exstcap.txt	AEO2014
coalPfac	CALBSC	All except iron and steel, paper, and aluminum	Factor to multiply by price to account for non-price cost associated with coal use	AEO2012
CON_Proxy_Wt	CONTPC	Construction	Shares of each construction activity (buildings, civil engineering, trade) by fuel	AEO2014
delta_sm	AL_smelt_alloc	Aluminum	Coefficient used to calculate aluminum smelting energy consumed based on aluminum smelting output and other variables; energy use decreases when coefficient value increased	AEO2013
domprod_IBYR	AL_prim_Smelt, AL_sec_prd	Aluminum	Total aluminum production (physical quantity) in 2005	AEO2013
domprod_IBYR2	AL_prim_Smelt, AL_sec_prd	Aluminum	Total aluminum production (physical quantity) in 2006	AEO2013
MetlShr	OTH_MINTPC	Mining	Share of other mining (metal and minerals) that is metal mining	AEO2016
ngasPfac	CALBSC	All except iron and steel, paper, and aluminum	Factor to multiply price to reflect natural gas as premium fuel	AEO2012
OGSM_MAP	OGSMTPC	Oil and natural gas industries	Maps OGSM (Oil and Gas Supply Module) regions to census regions	AEO2014
oilPfac	CALBSC	All except iron and steel, paper, and aluminum	Factor to multiply price to account for non-price costs of residual fuel oil	AEO2012
Printnem	INDSIC	All	Controls which fuels are printed in output tables	AEO2019
PROD_WT	OGSMTPC	Oil and natural gas industries	Weights used to calculate total oil and gas production	AEO2013
PRODX_BASE	PRODFLOW_PAPER	Paper	Physical paper production, 2014	AEO2018

Variable	Subroutine(s)	Industry	Explanation	Last update
RegCHPScore	CALGEN	All except iron and steel, paper, and aluminum	Regional CHP penetration adjustment based on ACEEE Scorecard friendliness factor	AEO2012
SurvBaseCapIBYR	AL_alloc	Aluminum	2014 surviving baseline capacity in 2014	AEO2013
TPC_Fac_Wt	OGSMTPC	Oil and natural gas industries	Shares of energy use by OGSM region by use (Vehicles, Production Factor, Dry Well index)	AEO2013
Weight_AG	AGTPC	Agriculture	Regional shares of energy consumption by buildings, vehicles, and irrigation	AEO2014
WEIGHT_CON	CONTPC	Construction	Regional shares of energy consumption by buildings, civil engineering, and trade	AEO2014
WPrep_Initial, WPrep_Final	PRODFLOW_PAPER	Paper	PRODFLOW coefficients for mechanical pulp, semi-chemical pulp, and Kraft pulp 2010 and 2020, respectively	AEO2016

Source: U.S. Energy Information Administration

Appendix C. Descriptions of Major Industrial Groups and Selected Industries

This appendix contains descriptions of industrial groups and selected industries taken from the North American Industry Classification System (NAICS). This appendix includes general descriptions of the 15 manufacturing and 6 non-manufacturing groups that comprise the industries modeled in the Industrial Demand Module. NAICS is the standard used by federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy.

NAICS 11—The **Agriculture, Forestry, Fishing, and Hunting** sector comprises establishments primarily engaged in growing crops, raising animals, harvesting timber, and harvesting fish and other animals from a farm, ranch, or their natural habitats.

The establishments in this sector are often described as farms, ranches, dairies, greenhouses, nurseries, orchards, or hatcheries. A farm may consist of a single tract of land or a number of separate tracts, which may be held under different tenures. For example, one tract may be owned by the farm operator and another rented. The tract may be operated by the operator alone or with the assistance of members of the household or hired employees, or it may be operated by a partnership, corporation, or other type of organization. When a landowner has one or more tenants, renters, croppers, or managers, the land operated by each is considered a farm.

The sector distinguishes two basic activities: agricultural production and agricultural support activities. Agricultural production includes establishments performing the complete farm or ranch operation, such as farm owner-operators, tenant farm operators, and sharecroppers. Agricultural support activities include establishments that perform one or more activities associated with farm operation, such as soil preparation, planting, harvesting, and management, on a contract or fee basis.

NAICS 21—The **Mining, Quarrying, and Oil and Gas Extraction** sector comprises establishments that extract naturally occurring mineral solids, such as coal and ores; liquid minerals, such as crude petroleum; and gases, such as natural gas. The term mining is used in the broad sense to include quarrying, well operations, beneficiating (for example, crushing, screening, washing, and flotation), and other preparation customarily performed at the mine site, or as a part of mining activity.

The Mining, Quarrying, and Oil and Gas Extraction sector distinguishes two basic activities: mine operation and mining support activities. Mine operation includes establishments operating mines, quarries, or oil and natural gas wells on their own account or for others on a contract or fee basis. Mining support activities include establishments that perform exploration (except geophysical surveying) and/or other mining services on a contract or fee basis (except mine site preparation and construction of oil and natural gas pipelines).

Establishments in the Mining, Quarrying, and Oil and Gas Extraction sector are grouped and classified according to the natural resource mined or to be mined. Industries include establishments that develop the mine site, extract the natural resources, and/or those that beneficiate (that is, prepare) the mineral mined. Beneficiation is the process whereby the extracted material is reduced to particles that can be

separated into mineral and waste, the former suitable for further processing or direct use. The operations that take place in beneficiation are primarily mechanical, such as grinding, washing, magnetic separation, and centrifugal separation. In contrast, manufacturing operations primarily use chemical and electrochemical processes, such as electrolysis and distillation. However, some treatments, such as heat treatments, take place in both the beneficiation and the manufacturing (that is, smelting and refining) stages. The range of preparation activities varies by mineral and the purity of any given ore deposit. While some minerals, such as petroleum and natural gas, require little or no preparation, others are washed and screened, while yet others, such as gold and silver, can be transformed into bullion before leaving the mine site.

NAICS 23—The **Construction** sector comprises establishments primarily engaged in the construction of buildings or engineering projects (for example, highways and utility systems). Establishments primarily engaged in the preparation of sites for new construction and establishments primarily engaged in subdividing land for sale as building sites also are included in this sector.

Construction work done may include new work, additions, alterations, or maintenance and repairs. Activities of these establishments generally are managed at a fixed place of business, but they usually perform construction activities at multiple project sites. Production responsibilities for establishments in this sector are usually specified in (1) contracts with the owners of construction projects (prime contracts) or (2) contracts with other construction establishments (subcontracts).

NAICS 311—Industries in the **Food Manufacturing** subsector transform livestock and agricultural products into products for intermediate or final consumption. The industry groups are distinguished by the raw materials (generally of animal or vegetable origin) processed into food products.

The food products manufactured in these establishments are typically sold to wholesalers or retailers for distribution to consumers, but establishments primarily engaged in retailing bakery and candy products made on the premises not for immediate consumption are included.

NAICS 321—Industries in the **Wood Product Manufacturing** subsector manufacture wood products, such as lumber, plywood, veneers, wood containers, wood flooring, wood trusses, manufactured homes (that is, mobile homes), and prefabricated wood buildings. The production processes of the Wood Product Manufacturing subsector include sawing, planing, shaping, laminating, and assembling of wood products starting from logs that are cut into bolts, or lumber that then may be further cut, or shaped by lathes or other shaping tools. The lumber or other transformed wood shapes may also be subsequently planed or smoothed, and assembled into finished products, such as wood containers. The Wood Product Manufacturing subsector includes establishments that make wood products from logs and bolts that are sawed and shaped, and establishments that purchase sawed lumber and make wood products. With the exception of sawmills and wood preservation establishments, the establishments are grouped into industries mainly based on the specific products manufactured.

NAICS 322—Industries in the **Paper Manufacturing** subsector make pulp, paper, or converted paper products. The manufacturing of these products is grouped together because they constitute a series of vertically connected processes. More than one is often carried out in a single establishment. There are essentially three activities. The manufacturing of pulp involves separating the cellulose fibers from other impurities in wood or used paper. The manufacturing of paper involves matting these fibers into a sheet. Converted paper products are made from paper and other materials by various cutting and shaping techniques and include coating and laminating activities.

The Paper Manufacturing subsector is subdivided into two industry groups, the first for the manufacturing of pulp and paper and the second for the manufacturing of converted paper products. Paper making is treated as the core activity of the subsector. Therefore, any establishment that makes paper (including paperboard), either alone or in combination with pulp manufacturing or paper converting, is classified as a paper or paperboard mill. Establishments that make pulp without making paper are classified as pulp mills. Pulp mills, paper mills and paperboard mills comprise the first industry group.

Establishments that make products from purchased paper and other materials make up the second industry group, Converted Paper Product Manufacturing. This general activity is then subdivided based, for the most part, on process distinctions. Paperboard container manufacturing uses corrugating, cutting, and shaping machinery to form paperboard into containers. Paper bag and coated and treated paper manufacturing establishments cut and coat paper and foil. Stationery product manufacturing establishments make a variety of paper products used for writing, filing, and similar applications. Other converted paper product manufacturing includes, in particular, the conversion of sanitary paper stock into such things as tissue paper and disposable diapers.

NAICS 325—The **Chemical Manufacturing** subsector is based on the transformation of organic and inorganic raw materials by a chemical process and the formulation of products. This subsector distinguishes the production of basic chemicals that comprise the first industry group from the production of intermediate and end products produced by further processing of basic chemicals that make up the remaining industry groups.

NAICS 326—Industries in the **Plastics and Rubber Products Manufacturing** subsector make goods by processing plastics materials and raw rubber. The core technology employed by establishments in this subsector is that of plastics or rubber product production. Plastics and rubber are combined in the same subsector because plastics are increasingly being used as a substitute for rubber; however the subsector is generally restricted to the production of products made of just one material, either solely plastics or rubber.

Many manufacturing activities use plastics or rubber, for example the manufacture of footwear or furniture. Typically, the production process of these products involves more than one material. In these cases, technologies that allow disparate materials to be formed and combined are of central importance in describing the manufacturing activity. In NAICS, such activities (the footwear and furniture manufacturing) are not classified in the Plastics and Rubber Products Manufacturing subsector because the core technologies for these activities are diverse and involve multiple materials.

NAICS 327—The **Nonmetallic Mineral Product Manufacturing** subsector transforms mined or quarried nonmetallic minerals, such as sand, gravel, stone, clay, and refractory materials, into products for intermediate or final consumption. Processes used include grinding, mixing, cutting, shaping, and honing. Heat often is used in the process and chemicals are frequently mixed to change the composition, purity, and chemical properties for the intended product.

The Nonmetallic Mineral Product Manufacturing subsector includes establishments that manufacture products, such as bricks, refractories, ceramic products, and glass and glass products, such as plate glass and containers. Also included are cement and concrete products, lime, gypsum and other nonmetallic mineral products including abrasive products, ceramic plumbing fixtures, statuary, cut stone products, and mineral wool. The products are used in a wide range of activities from construction and heavy and light manufacturing to articles for personal use.

The IDM models the following three industries in NAICS 327 (see Table 2 on page 8 for exact NAICS codes in each industry).

> The **Cement Manufacturing** industry (see Table 2 on page 8 for exact NAICS codes) constitutes establishments primarily engaged in manufacturing portland, natural, masonry, pozzolanic, and other hydraulic cements. Cement manufacturing establishments may calcine earths or mine, quarry, manufacture, or purchase lime.

> The **Lime Manufacturing** industry, reported jointly with cement, constitutes establishments primarily engaged in manufacturing lime from calcitic limestone, dolomitic limestone, or other calcareous materials, such as coral, chalk, and shells. Lime manufacturing establishments may mine, quarry, collect, or purchase the sources of calcium carbonate.

> The **Glass Manufacturing** industry produces glass is produced by heating silica sand to the melting point sometimes combined with cullet, or recycled glass. Establishments in this industry produce flat glass, blown glass, and container glass. The IDM also includes mineral wool, or fiber glass in the glass model. Mineral wool is NAICS 32799.

NAICS 331—Industries in the **Primary Metal Manufacturing** subsector smelt and/or refine ferrous and nonferrous metals from ore, pig or scrap, using electrometallurgical and other process metallurgical techniques. Establishments in this subsector also manufacture metal alloys and superalloys by introducing other chemical elements to pure metals. The output of smelting and refining, usually in ingot form, is used in rolling, drawing, and extruding operations to make sheet, strip, bar, rod, or wire, and in molten form to make castings and other basic metal products.

Primary manufacturing of ferrous and nonferrous metals begins with ore or concentrate as the primary input. Establishments manufacturing primary metals from ore and/or concentrate remain classified in the primary smelting, primary refining, or iron and steel mill industries regardless of the form of their output. Establishments primarily engaged in secondary smelting and/or secondary refining recover ferrous and nonferrous metals from scrap and/or dross. The output of the secondary smelting and/or secondary refining industries is limited to shapes, such as ingot or billet, which will be further processed. Recovery of metals from scrap often occurs in establishments that are primarily engaged in activities such as rolling, drawing, extruding, or similar processes.

NAICS 332—Industries in the **Fabricated Metal Product Manufacturing** subsector transform metal into intermediate or end products, other than machinery, computers and electronics, and metal furniture, or treat metals and metal formed products fabricated elsewhere. Important fabricated metal processes are forging, stamping, bending, forming, and machining, used to shape individual pieces of metal; and other processes, such as welding and assembling, used to join separate parts together. Establishments in this subsector may use one or a combination of these processes.

NAICS 333—Industries in the **Machinery Manufacturing** subsector create end products that apply mechanical force, for example, the application of gears and levers, to perform work. Some important processes for the manufacture of machinery are forging, stamping, bending, forming, and machining that are used to shape individual pieces of metal. Processes, such as welding and assembling are used to join separate parts together. Although these processes are similar to those used in metal fabricating establishments, machinery manufacturing is different because it typically employs multiple metal-forming processes in manufacturing the various parts of the machine. Moreover, complex assembly operations are an inherent part of the production process.

NAICS 334—Industries in the **Computer and Electronic Product Manufacturing** subsector group establishments that manufacture computers, computer peripherals, communications equipment, and similar electronic products, and establishments that manufacture components for such products. The Computer and Electronic Product Manufacturing industries have been combined in the hierarchy of NAICS because of the economic significance they have attained. Their rapid growth suggests that they will become even more important to the economies of all three North American countries in the future, and in addition their manufacturing processes are fundamentally different from the manufacturing processes of other machinery and equipment. The design and use of integrated circuits and the application of highly specialized miniaturization technologies are common elements in the production technologies of the computer and electronic subsector. Convergence of technology motivates this NAICS subsector. Digitalization of sound recording, for example, causes both the medium (the compact disc) and the equipment to resemble the technologies for recording, storing, transmitting, and manipulating

data. Communications technology and equipment have been converging with computer technology. When technologically-related components are in the same sector, it makes it easier to adjust the classification for future changes, without needing to redefine its basic structure. The creation of the Computer and Electronic Product Manufacturing subsector assists in delineating new and emerging industries because the activities that will serve as the probable sources of new industries, such as computer manufacturing and communications equipment manufacturing, or computers and audio equipment, are brought together. As new activities emerge, therefore, they are less likely to cross the subsector boundaries of the classification.

NAICS 335—Industries in the **Electrical Equipment, Appliance, and Component Manufacturing** subsector manufacture products that generate, distribute and use electrical power. Electric Lighting Equipment Manufacturing establishments produce electric lamp bulbs, lighting fixtures, and parts. Household Appliance Manufacturing establishments make both small and major electrical appliances and parts. Electrical Equipment Manufacturing establishments make goods, such as electric motors, generators, transformers, and switchgear apparatus. Other Electrical Equipment and Component Manufacturing establishments make devices for storing electrical power (for example, batteries), for transmitting electricity (for example, insulated wire), and wiring devices (for example, electrical outlets, fuse boxes, and light switches).

NAICS 336—Industries in the **Transportation Equipment Manufacturing** subsector produce equipment for transporting people and goods. Transportation equipment is a type of machinery. An entire subsector is devoted to this activity because of the significance of its economic size in all three North American countries.

Establishments in this subsector use production processes similar to those of other machinery manufacturing establishments—bending, forming, welding, machining, and assembling metal or plastic parts into components and finished products. However, the assembly of components and subassemblies and their further assembly into finished vehicles tends to be a more common production process in this subsector than in the Machinery Manufacturing subsector.

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