# Industrial Energy Consumption Forecasting: The Things that Matter

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## ABSTRACT

Changes in the use of materials are responsible for changes in levels and patterns of energy consumption in the industrial sector. However, with the exception of only a very few modeling efforts, the linkage between energy consumption and materials has not been incorporated into energy modeling frameworks. As a result, energy system models for the industrial sector focusing only on energy, often miss-forecast critical changes in levels of energy consumption or types of energy consumed resulting from changes in material use either as an input or an output. Within the framework of a US energy system model (MARKAL), where all sources of energy supply and demand are depicted, the potential impacts of the inclusion of materials on industrial energy consumption trends has been investigated. This discussion will examine the benefits of utilizing a materials-enhanced framework. As an example, the focus will be on the iron and steel sector, and illustrate how recycled materials, material input substitution, imports of intermediate inputs, and to some extent how changes in product demand affect energy consumption. As a result, energy intensity reductions can be attributed to improvements in the energy efficiency of technology as opposed to other changes. Also, the costs of developing such a framework and the limitations particularly when considering the longer term will be considered. Examining both the benefits and limitations of a materials-enhanced framework suggest future strategies for industrial energy modeling development.

## Introduction

Decomposition of energy trends, specifically aggregate energy intensity trends, is often one of the first analysis exercises when studying industrial or, more specifically, manufacturing energy. From these evaluations, analysts have determined that changes in economic structure impact energy trends over time as do changes in energy intensity (Ang 1995; Greening et al. 1997; Liu & Ang 2007). However, the factors that affect energy intensity have not been well explained. The common misconception has been that technical energy efficiency probably explains the majority of decreases in manufacturing energy over time. However, when placed in an economic context, where we consider relative prices of factor inputs in the measurement of productivity improvements, energy probably plays a smaller role than believed.

The observation has been made that the cost share represented by materials and other intermediate inputs is substantially larger than any of the other inputs including energy. On an aggregate basis in the US, the cost share for materials is somewhere on the order of 12 times that for energy in the production of a unit of output (Berndt & Wood 1975). Further, for many of the industries that we refer to as ‘energy intensive’ (e.g., primary metals), productivity has grown from activities designed to reduce materials consumption rather than energy (Jorgenson 1995). Finally, that materials and energy may be either a weak substitute or a weak complement in disaggregated econometric estimates of production functions. But, more often for ‘energy intensive’ manufacturing, energy and materials exhibit complementarity (Jorgenson & Fraumeni

1981). This would imply that a reduction in materials usage should also result in some reduction in energy consumption.

From the materials perspective, it has been observed that changes in material types and usage in final products can affect the levels of energy consumed (Cleveland & Ruth 1999). Levels of energy consumption in many of the 'energy intensive' industries have been and will be reduced through technological improvements and the recycling of materials (Ruth 1995, 1998). As noted in longer-run evaluations of technological change, industrial firms respond to incentives (i.e., minimize costs of production) to reduce materials consumption which in turn reduces energy consumption and the accompanying environmental impacts (Grubler 1987, 1994, 1998). Further, it has been observed that changes in efficiency of material use in one sector spread through the economy affecting both energy and material use in other sectors (Cleveland & Ruth 1999). As part of that observation, imports of semi-finished and finished goods serve as an embodied source of energy which can result in a lower apparent energy intensity of production. Finally, changes in the final demand for the mix of products (materials) produced by an economy can alter the demand for energy for industrial purposes. Some of these changes in final demand can actually lead to a 'rebound' affect in materials consumption, which in turn could lead to a 'rebound' in energy in a broader macroeconomic sense (Greening et al. 2000). Therefore, understanding and modeling materials consumption has a number of direct implications for understanding industrial energy consumption.

Given these observations on the linkages and interaction(s) between energy and materials consumption, the question naturally occurs: Why do we continue to model only energy in energy-system models? In the few examples available of models that depict both energy and materials, it has been shown that the inclusion of materials results in a more all-inclusive evaluation and improved forecasts of future industrial energy consumption (Gielen & Karbuz 2003). The remainder of this discussion will focus on the inclusion of materials in an energy-system model for the US. To illustrate the benefits of such an activity, this paper will focus on the iron and steel sector. Observations from an examination of such a specific example can be easily expanded to other sectors. Further, comments will be made on the difficulties of obtaining adequate information on materials consumption. From this discussion, it may be concluded that inclusion of materials is an important component of an energy-system model and should be embraced in future development activities for various frameworks.

## Description of Modeling Framework

MARKAL (MARKet Allocation model) is a technology-oriented energy system model, which utilizes a dynamic linear programming framework where all energy supplies and demands for energy services are depicted (Fishbone & Abilock 1981). Technologies within the modeling framework are described by initial investment, operating and maintenance (fixed and variable) costs, capacity utilization or availability depending upon the technology type, and the efficiency (or heat rate in the case of electricity generation) of fuel use. As is typical of energy system models, energy flows are conserved, all demands are satisfied, previous investments in technologies are preserved, peak-load electricity requirements are honored, and capacity limits are observed. Where applicable other similar traits of an energy system are included. Technologies are selected for inclusion in the solution based on comparison of life-cycle costs of alternative investments. In the standard variant, MARKAL minimizes energy system (capital, operating, and fuel) costs over the entire planning horizon; other variants such as MARKAL-

Elastic Demand (MED) allow the inclusion of a price response (for an overview of the family, see Goldstein & Greening 1999). Also, MARKAL provides an accounting mechanism for emissions by either the application of emissions coefficients on fuel consumption and/or on per unit output of a conversion, processing, or demand technology.

MARKAL is implemented in over 40 countries around the world, and at least two world models using the framework have been developed. In addition to different scopes of coverage, each version of MARKAL can be distinguished by the level of development and detail depicted in its database. For the US, several different versions have been developed. This paper will discuss the LA US-MARKAL.[1] LA US-MARKAL includes a number of features that assist in the analysis of a broad spectrum of energy-related issues. Some of the features include:

- Technology choice set of well over 4000 technologies representing energy conversion (electricity generation), energy and materials processing, and energy service demand.

- Resource set including not only conventional fossil resources (e.g., coal, oil, natural gas), and renewable resources (e.g., wind, solar), but also longer-term unconventional resources (e.g., methane hydrates, oil shale).

- Nine different emissions types ($CO_2$, $SO_2$, $NO_x$, CO, VOC, $CH_4$, particulates, and mercury) are tracked through the economy; and, several of the key emissions are by sector of emission, e.g., $CO_2$ from transportation energy consumption.

- Inclusion of a demand-specific response to prices and income, i.e., micro-level as opposed to macro-level. Incorporation of this response usually results in lower total energy demand.

- Time horizon for LA US-MARKAL extends from 1995 to 2100. This longer forecast horizon allows for the analysis of the effects of depletion of resources of both conventional energy resources and other natural resources such as materials.

The base year used in this work is 1995 (i.e., all costs are in $1995 US) while energy service demands and other parameters are consistent with AEO 2006 ([EIA] Energy Information Administration 2006). The forecast horizon is divided into five year periods, and the resulting forecast values of energy consumption, and other outputs represent a 5-year average at the mid-point of a period. Forecasts generated using this version of the model start in 1995, and as a result three periods of actual data are used to calibrate or 'set' the model for solution.

## General Industrial Sector Depiction

The industrial sector in LA US-MARKAL has been disaggregated into thirteen distinct sub-sectors. Eleven of the thirteen sub-sectors are characterized by a process train description utilizing well over 2400 technologies. The industrial specification in LA US-MARKAL parallels

[1] LA US-MARKAL is one of at least four US MARKAL models currently in existence or under development. Each model has a different forecasting horizon, and is designed to evaluate a different set of problems. If the reader has a particular interest in determining which model is the "best," direct contact with the developers is recommended. Of course, the reader should be forewarned that each set of developers would claim "superiority."

the well-established industrial energy model, ITEMS (Industrial Technology and Energy Modeling System), and is calibrated to MECS 1994, 1998, and 2002 ([EIA] Energy Information Administration 1997, 2000, 2004). The original ITEMS data set (Energy and Environmental Analysis Inc. 1983) was supplemented with the data set currently underlying CIMS ([CIEEDAC] Canadian Industrial End-Use Energy and Data Analysis Center 2006), and was updated where possible with additional technology characterizations from the literature.

The industrial specification in LA US-MARKAL offers a number of benefits for the analysis of industrial energy. This specification of industrial energy consumption conforms to the intent of the original MARKAL developers (Hamilton et al. 1992); and, has been previously implemented in other national MARKAL frameworks such as the Japanese model (Sato et al. 2000; Sato et al. 1998), the Western European Matter model (Gielen et al. 1998), and the IEA's Energy Technology Perspectives model (Gielen & Taylor 2007). The advantages from this approach include:

- Use of this specification results in a more realistic depiction of the derived demand for industrial energy (e.g., mechanical drive powers pumps, fans, compressors, conveyors and other process associated equipment). And, as a result, endogenous estimates of specific auxiliary services are generated (Jaccard & Roop 1990; Murphy et al. 2007).

- More points in the system or sector where industrial energy consumption is reduced by technological improvements, and the interactions between different technologies and materials input substitution are captured (Jaccard & Roop 1990; Murphy et al. 2007).

- The platform can be readily used to test for the effects of increases in the energy efficiency of specific industrial technologies, new technologies, changes in material inputs, or process improvements (Gielen & Taylor 2007).

- As part of the 'process train' specification, energy service demands are expressed in terms of physical units of product output or GDP where appropriate. Use of physical output as a measure of energy services provides for a ready linkage to other economic frameworks such as an input/output (I/O) or computable general equilibrium (CGE) framework (Schumacher & Sands 2007). Further using physical units means that the drivers energy is forecast on variables independent of the energy system (i.e., energy consumption is not forecast on energy demand).

- Disaggregated demands or explicit depiction of the product mix output from an industrial sector allows for the investigation of the effects of economic structural change on the output from some sectors (Cleveland & Ruth 1999).

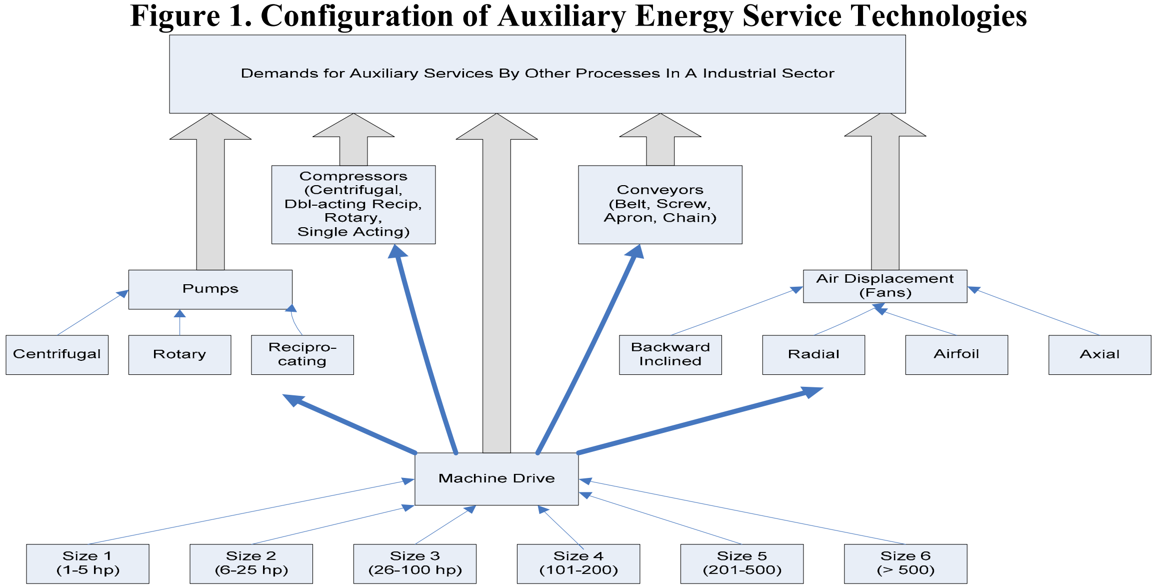
- Output from combined heat and power (CHP) is determined by the total requirements for electricity and heat for the production of demanded output. However, the share of electricity as opposed to heat or steam is flexible within technology constraints, and is determined by inter-technology competition. For electricity, CHP competes with grid sourced electricity (Greening & Schneider 2003); for steam and process heat, CHP competes with standard boilers fueled by natural gas, coal, and distillate fuels.

- Fuel sources for a technology are selected on the basis of the life-cycle costs of the entire process train, including materials where specified, subject to environmental and other constraints.

As a result of this type of formulation for the modeling of industrial energy consumption, particularly with the inclusion of materials, we are able to address the linkages between materials and energy consumption, and expand the power of our analysis.

Every industrial sector in LA US-MARKAL has a similar configuration for auxiliary services. Auxiliary services include the energy services provided by motors, compressors, fans or air displacement, conveyors, pumps, and direct process drives. Figure 1 illustrates the relationships between those technologies and the rest of the system. Due to limitations on space, only the intermediate nodes or higher nodes are presented; direct process drives are not included on this figure although they also provide auxiliary services. Compressor and conveyors have similar configurations to pumps, air displacement or motors in terms of intermediate nodes for each technology type below the primary node. In addition, pumps and compressors have two size nodes below each technology-type node. Specific technologies, e.g., low, medium, and high efficiency centrifugal compressors of size 1, are at the lowest tier of the tree structure. The number of technologies in the lowest tier may vary. For example, two levels of efficiency are depicted under Size 1 machine drive (motors), while under sizes 5 and 6, six different technologies for each size are depicted; these technologies include standard and efficient AC induction, synchronous induction, direct current generator and solid state, and steam driven motors. The market share of each technology-size class is determined by a set of proportionality constraints across the intermediate size nodes; or, where appropriate between technology-type nodes, e.g., centrifugal, rotary, and reciprocating pumps. Penetration of specific technologies within a size class and technology type is determined by the life-cycle costs, i.e., competition between technologies serving the same service niche without constraint. Since sizes of technologies such as motors vary across industries, each industrial sector has a specific set of constraints capturing that difference.

**Figure 1. Configuration of Auxiliary Energy Service Technologies**



Other process technologies in a sector have engineering parameters describing the use of a specific auxiliary technology. For example, basic oxygen furnaces (BOFs) use auxiliary services from pumps, air displacement, compressors, and conveyors which all in turn use machine drive services from motors. As a result, demand for a specific auxiliary technology is dependent on the level of demand for a final output from a sector.

There are several other parameters found in all of the industrial sectors. Costs and variable operating costs (excluding materials) were taken primarily from the ISTUM and CIMS databases. Since both of those models assume triangular distributions of costs, but MARKAL requires a deterministic or single point estimate, weighted costs at the mean of the distribution were calculated and used in MARKAL. Introduction of additional technologies required scaling to an appropriate basis within each sub-set of technologies. Also, all technologies have technology-specific discount rates. Unlike other sectors, where such analysis has been performed, data supporting this parameter is sparse. Therefore, hurdle rates observed for capital rationing firms for projects of different sizes were used as a starting point (Ross 1986). These values were then adjusted during calibration to the 1994, 1998, and 2002 Manufacturing Energy Consumption Surveys ([EIA] Energy Information Administration 1997, 2000, 2004). This is admittedly an imperfect approach, and when further research is available will be re-evaluated.

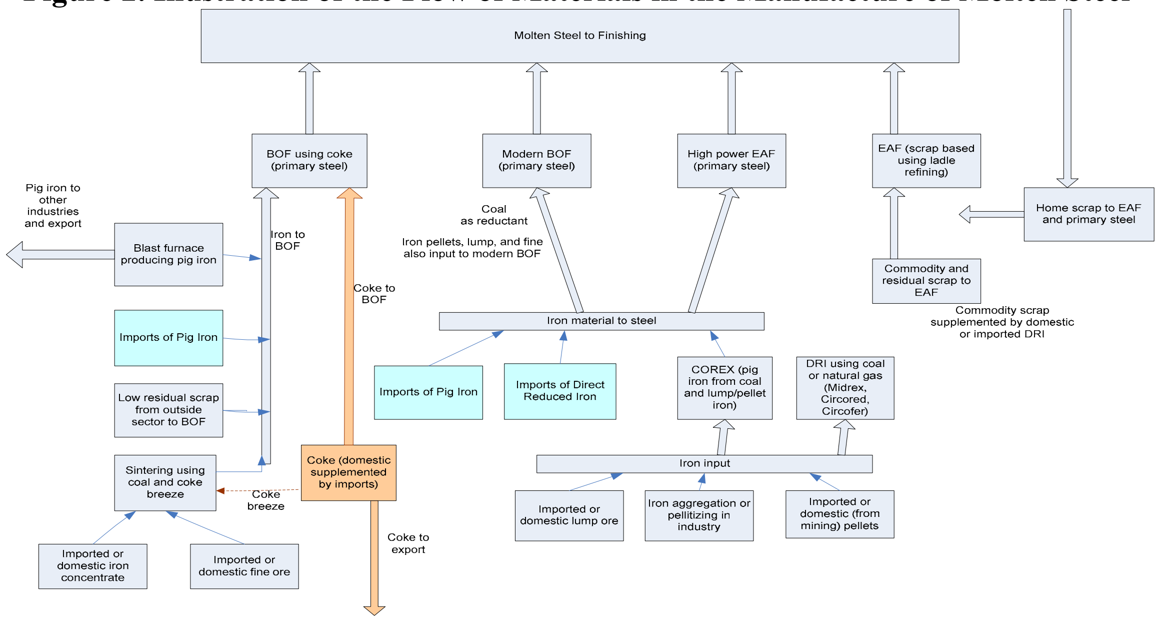
## Depiction of Iron and Steel Industry

Figures 2 and 3 provide schematic flow diagrams of materials for iron and steel, one of the industrial sectors currently depicted in LA US-MARKAL. This diagram illustrates relationships between technologies at a fairly high-level. Within specific technology groups providing the same output, individual technologies compete. For example within the groups labeled as 'BOFs using coke' and 'Modern BOF', twelve different BOF technologies compete in the production of molten steel. Technologies in this group are distinguished by fuels used, material inputs, investment and variable costs, and other parameters. This set of technologies in turn competes with a group labeled 'High power EAF' which produce primary steel from direct reduced iron (DRI) and pig iron. As illustrated in Figure 3, output from molten steel production feeds such operations as ingot, continuous casting, and thin slab casting, slab pickling, galvanizing, cold rolling, annealing, plating and similar operations for the production of finished and semi-finished steel products. For various stages of each of these process trains, home scrap is recycled back to the production of steel as an input.

Demands for this sector are specified as tons of slabs and slab products, heavy structural steel, tubes, bars, rods, and light structural shapes. As a result of this disaggregation of sector demand into categories of final products, structural shifts or changes in patterns of product demand can affect the over-all energy consumption in the sector, and the specific types of energy consumed. Constraints are used between technologies within groups to control capacity and activity. For example, a constraint provides for the trade-off between primary steel production and steel from recycled metal.

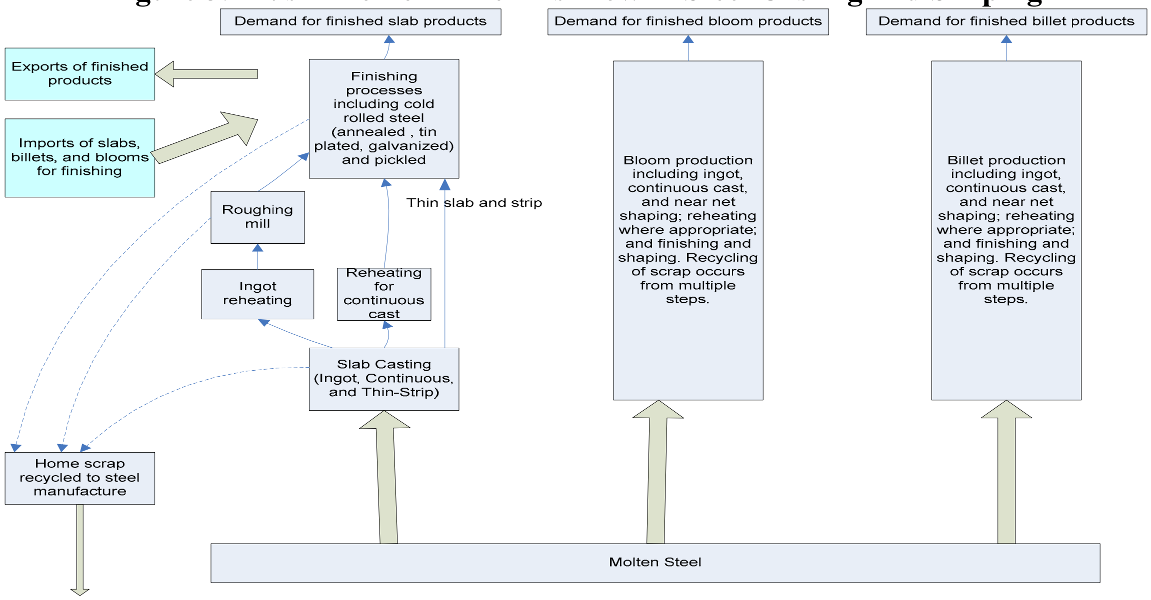
The pre-processing of material inputs depicted on this diagram highlights the value of including material inputs in the industrial sector of an energy system framework. For example, current BOF facilities use sinter, pellets, lump ore, direct reduced iron, and recycled low-residual and home scrap for iron input. The use of sinter to produce steel in the US has fallen by over 36% between 1995 and 2004 (Fenton 2004). Sintering uses nearly 3.25 times the energy used in pelletizing; and, that energy is in the form of coke and coke breeze. Because of this energy consumption, and the levels of particulates and other emissions associated with sintering, this process is gradually being abandoned.

**Figure 2. Illustration of the Flow of Materials in the Manufacture of Molten Steel**




With the penetration of modern technologies, the importance of material substitution in determining energy consumption cannot be over-emphasized. Modern BOFs utilizing pig iron from COREX processes or DRI from MIDREX, Circofer, or Circored processes utilize fine or lump ore rather than pellets (Daniels 2002). As a result, the costs and energy consumption of pre-processing are reduced by 16% to 30% (BCS 2002). Although, this reduction occurs in the primarily in the mining industry with only a minor amount in the steel sector, this type of interaction illustrates the ‘ripple effect through the economy of changes in material usage. For producers of steel, the switch to the use of lump or fine ore represents a cost savings of over 19% to 65% per unit of output (Jorgenson 2004). This savings is in addition to the energy savings. Modern BOFs use coal directly as a reductant, and as a result coke and the process of coking are no longer required. Further, energy consumption in a BOF is reduced by between approximately 7% and 60% (Daniels 2002). The material and energy savings together outweigh increase in the per unit capital cost of approximately 25% for a new BOF technology. To achieve even greater savings, the output of modern technologies used in the production of pig iron and direct reduced iron can be used in ultra high power EAFs to produce primary steel.

**Figure 3. Illustration of Materials Flow in Steel Casting and Shaping**




Similarly, as molten steel is processed into finished final output from the sector, by accounting for materials, specifically the scrap resulting from casting and finishing, energy consumption is reduced. For example, ingot casting has a scrappage rate of 7% or higher depending upon the vintage of the casting technology. On the other hand, continuous casting has a 4% scrappage rate, and thin slab has a rate closer to 1.25%. For every tonne of metal lost to scrappage from ingot casting, roughly 10.05 MMBTU is lost although some is recovered through reuse in steel making. Similarly, for every ton of metal lost from scrappage in continuous casting, 8.4 MMBTU is lost. Therefore, representing these differences in an industrial energy model is as important as representing the savings from the adoption of a new technology. Accounting for a reduction in loss, essentially doubles the apparent energy savings from adopting a new technology.

Imports can be a source of embodied energy, or rather imported materials represent avoided energy consumption in a national system. Recognizing this, in LA US-MARKAL imports of iron and semi-finished metal (i.e., slabs, blooms, and billets are represented). Currently, roughly 20% of the iron supply for the US is imported in one form or another (Jorgenson 2004). If imports were to decline (hypothetically to zero) then energy consumption for iron mining could increase as much as 15.5 Trillion BTU. Further, imported semi-finished metal accounts for approximately 6.7% of steel processed into finished product. Both of these examples illustrate that energy is embedded in imports, and should be represented in a modeling framework.

## Conclusions: Is the Effort Worth It?

From the foregoing discussion, energy-only models for the industrial sector do not capture a number of important factors in determining aggregate levels of energy consumption or the potential changes in energy intensity of an industrial sector. As illustrated by the example presented for the process of making steel, industrial energy is a derived demand. This demand is a function of the amount of finished product produced from a process including potentially any number of combinations of different technologies. Any change in that process, could reduce sector energy consumption. Models where a specific energy demand, such as motor drive, is exogenously forecast by the analyst do not adequately depict this complexity.

These missing factors have implications for the adoption of a technology. As our example for iron and steel has illustrated, reduction of costs from the change in materials inputs probably have a greater role in the decision process than energy savings alone. Materials represent a much greater contribution to total production costs than energy, and as a result, operators of manufacturing facilities focus on reducing those costs. Those reductions can come from changes in material inputs, such as the substitution of coal for coke in primary steel manufacture, or from the reduction of the scrappage rate during finishing. Therefore, inclusion of materials in a modeling framework captures operating decisions to a greater extent. Thus, inclusion of materials should improve forecasts of manufacturing energy consumption, and provide greater insight into the technologies that might be adopted.

These missing factors have potential policy implications. For example, the increasing use of imported semi-finished or intermediate inputs has meant that for certain industrial sectors in the US energy intensities have continued to decline. Should for example, a climate policy be adopted, the importation of such materials would probably increase. US manufacturing energy intensity and overall manufacturing energy consumption would decline. As another example, a shift is naturally occurring from the use of coke to coal as a result of shifting to a less costly iron input. Greenhouse gas emissions (or the carbon intensity) from steel manufacturing is declining. As a result, arguably the need for specific regulation of this source is not as pronounced as would be perceived without an understanding of the manufacturing decision process.

However, the inclusion of materials adds an additional level of complexity to the modeling framework. For the majority of ‘energy intensive’ industries in the US, publicly available data is available on material flows and the inputs to specific technologies. Collecting and synthesizing this data to add to an existing framework probably increases effort by at least half-again. However, in so doing, more behaviors are captured. Also, the modeling framework benefits on a very practical stand-point. Tracking the flows of materials through a system provides an additional means of calibrating a modeling framework. As our example from iron and steel illustrates, materials flow in and out of the sector at various points. Failure to account for those movements will result in either under-estimating or over-estimating energy consumption. Hopefully, the foregoing has made sufficient argument for the expansion of energy-only models for industrial energy to incorporate materials.

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