A New Benchmark of Energy Performance for Energy Management in U.S. and Canadian Integrated Steel Plants

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ABSTRACT

ENERGY STAR® is a market-based program managed by the U.S. Environmental Protection Agency (EPA) that supports businesses and consumers by making it easier to save money and protect the climate through superior energy efficiency. The familiar ENERGY STAR label can be found on high-performing appliances, office equipment, lighting, buildings, manufacturing plants and more. Within the industrial sector, the ENERGY STAR program focuses on enabling sustainable corporate energy management. A key ENERGY STAR energy management tool provided to industries is a plant Energy Performance Indicator (EPI). An EPI is a statistical benchmarking tool that provides a “birds-eye” view of a plant’s sector-specific plant-level energy use via a functional relationship between the level of energy use and the level and type of various production activities, material input's quality, and external factors, such as climate. The EPI uses a standard linear regression model to estimate the lowest observed plant energy use, given these factors. This statistical model also provides a distribution of energy efficiency across an industry, allowing users to answer the very practical question, “How would my plant’s energy performance compare to that of others in my industry *if all other plants* were similar to mine?” Corporate and plant energy managers in eleven manufacturing industries in the U.S. use ENERGY STAR EPIs to estimate the energy efficiency of their plants, set improvement goals, inform investment decisions, and earn recognition for good performance through EPA. More than a dozen additional industries are working with EPA to develop ENERGY STAR EPIs for their plants. This paper describes the development of the first EPI for evaluating the energy performance of integrated steel mills in the U.S. and Canada.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) manages ENERGY STAR, a market-based program that supports businesses and individuals in saving money and protecting the climate through superior energy efficiency. Begun in the early 1990’s, this voluntary program works with businesses to evaluate the unique conditions that impact energy efficiency in specific industrial sectors and then strives to help these industries overcome the barriers to adoption of cost-effective solutions in energy management. Within the industrial sector, the main consumer of energy is the manufacturing plant and operations within that facility. EPA promotes a proven strategy for managing energy across all operations and achieving the cost savings and environmental benefits that can result from implementing a strong energy management program. ENERGY STAR tools and resources help improve energy efficiency in the industrial sectors by providing:

- A credible and objective scoring system to assess the energy performance of plants, validate savings, and recognize top performance,
- Sector-specific guides on how to reduce energy consumption in manufacturing plants, and,
- Access to a broad network of ENERGY STAR industrial partners, bringing fresh, diverse and creative approaches to managing energy.

In the manufacturing sectors, improving energy efficiency depends on knowing how to improve and how much to improve. EPA has found that many companies want to understand how much can be done to improve their plants’ energy performance. Others resign themselves to accept the premise that what cannot be measured cannot be managed. EPA has overcome these limitations by working with individual industries to develop ENERGY STAR plant Energy Performance Indicators (EPIs) to benchmark the performance of whole plants and to answer the question of how much to improve a plant's performance. EPA's national system of evaluating plant energy performance enables users to manage energy at a level not previously possible. Businesses use ENERGY STAR EPIs to identify individual facilities for improvement, set energy performance goals, learn from efficient facilities identified with the ENERGY STAR, and earn positive recognition. Plants where energy performance is within the top quartile nationally for an industry are eligible to earn ENERGY STAR certification and display the ENERGY STAR banner or flag (See Figure 1).

Unique Resources for Steel Producing Plants

EPA works with steel producers through the ENERGY STAR Focus on Energy Efficiency in Iron & Steel Manufacturing (hereafter the "Steel Focus"), an ENERGY STAR-hosted energy management community of practice that looks at the barriers to energy efficiency and builds tools and strategies to help reduce the impact of these barriers. EPA's ENERGY STAR Steel Focus builds useful energy management tools for the industry including energy management guidance and an EPI for integrated steel mills. One tool that addresses the barrier of how to improve is the ENERGY STAR Energy Guide for the steel industry [1]. The Energy Guide identifies opportunities for improving efficiency. Examples of the types of improvement measures identified for steel mills are identified in Table 1.

Another energy management tool developed through the Steel Focus is a steel plant EPI. The EPI answers how well a plant could perform. This statistical model enables companies to judge the energy efficiency of individual integrated steel mills. EPIs model the energy performance of integrated mills within the entire industry and produce an energy performance score for an integrated mill within the industry in the United States and Canada.

Figure 1. ENERGY STAR Certified Cement Plant

Table 1. Improvement opportunities identified for steel plants. (see [1])

Cross-cutting technologies	Process Areas Discussed
Motors	Heat recovery
Pumps	Blast furnace measures
Fans	Basic Oxygen Furnace measures
Compressed air	Electric Arc Furnace measures
Cogeneration	Casting & Refining
Boilers & steam systems	Hot & Cold Rolling

DEVELOPING AN EPI FOR INTEGRATED STEEL

The steel industry is not new to "energy benchmarking." Some other examples include [2-6]. This section describes the concept of "Benchmarking" used to develop the EPI for integrated steel, the underlying statistical methodology, and how the approach is used to create an ENERGY STAR Energy Performance Score (EPS).

Defining an ENERGY STAR EPI

When ENERGY STAR began working with industry to help identify good plant energy performance, the term "plant benchmark" was discussed. Industry engineers routinely develop benchmarks at many levels of plant operation, but concern was expressed that using the word "benchmark" would be confusing and could imply a particular process or tool. For this reason, it was decided that a simple descriptive term would be clearer; thus, ENERGY STAR plant energy performance indicator (EPI) was adopted. The scope for the EPI is a plant-level indicator, not process-specific, and it relates plant inputs in terms of all types of energy use to plant outputs as expressed in a unit of production. Years of discussions with many industry representatives has helped to define the energy focus of the models that EPA produces through ENERGY STAR.

Efficiency is a measure of relative performance; but relative to what? Defining energy efficiency requires a choice of a reference point against which to compare energy use. Energy efficiency measures can be developed through a variety of sources, such as engineering and theoretical estimates of performance or through observing the range of actual levels of performance. The choice of method used to define efficiency depends on the need to define a reference point for energy efficiency. One of the challenges with using energy efficiency benchmarks based on engineering or theoretical estimates is that they are often dismissed as being economically infeasible.

Consequently, EPA through ENERGY STAR has focused on developing benchmarks based on actual or observed operational performance rather than theoretical estimates of potential efficiency levels. Additionally, EPA needed to identify a benchmarking method that would be perceived by end users as economically feasible which is important for the adoption of the benchmarking system and ultimately its impact on driving change.

When making inter-plant comparisons, it is necessary to consider a variety of factors that do not fit neatly under the denominator of an energy intensity ratio. While all plants may make a common product, other differences can significantly affect energy intensity. The difficulty with applying an industry level inter-plant benchmark is controlling for inter-plant differences other than production volumes. While the things that differ between plants are numerous, we have found that the primary differences that have the most impact on energy fall into the following categories:

- Product mix
- Process inputs
- Size - Physical or productive capacity and utilization rates
- Climate (and other location specific factors)

The choice of factors to include in the analysis depends upon the nature of the production process, the configuration of the industry (e.g. is upstream integration common or rare), the availability of data to represent these factors, and ultimately the outcome of the statistical tests for significance. In order to address these types of factors, the ENERGY STAR EPI uses a multivariate approach to normalization where multiple effects are simultaneously considered. [7]

Statistical approach

The methodology underlying the analysis can be motivated by the concept that there is some reduced form of relationship between plant level energy use and the various plant input and output characteristics described below. We assume that this relationship can be approximated by a functional form that is amenable to statistical estimation using data from a cross section or panel of plants within some "reasonably defined" industry group. Depending on the form of the statistical model, discussed in more detail below, the actual plant energy use can then be compared to the predicted average, given the plant's characteristics. How far the actual energy use is above or below the predicted average is the plant's measure of efficiency. In statistical terms, the difference between actual and predicted energy use is equal to the residual of the statistical model for plants that are in the sample; alternatively this difference is an out-of-sample prediction when the statistical model is applied to other data. It is in this out-of-sample context that we expect the model to be most often used, i.e., to compute energy efficiency using data for plant level operations that were not in the statistical analysis, possibly from a different year. If that is the case then the model is measuring current performance to a prior "benchmark year." If we further assume that the estimated distribution of efficiency from the statistical model is static then the out-of-sample prediction of efficiency can be converted to a percentile (ranking) of efficiency based on the estimated distribution. The approach applied here is similar to guidance from

ISO 50001 regarding the creation of EnPI[1], although the ENERGY STAR EPI approach predates the release of ISO 50001 [7-9]. Other applications of this approach include estimation of energy savings post-retrofit but using time series data for a single plant [10].

The concept of the analysis that supports the EPI can be easily described in terms of the standard linear regression model, which is reviewed in this section. Consider at first the simple example of a production process that has a fixed energy component and a variable energy component. A simple equation for this can be written as

$$E = f(Y, X; \beta) + \varepsilon \qquad (1)$$

Where E is the measure of total source energy (total Btu of fuels and electricity use converted to Btu based on average U.S. thermal plant efficiency including line losses), Y is either production or a vector of production related activities, X is a vector of plant characteristics, β is a parameter vector (the normalization factors) and ε is the measure of relative plant efficiency.

Given data on energy use and production, the parameters can be fit via a linear regression model. Since the actual data may not be perfectly measured and this simple relationship between energy and production is only an approximation of the "true" relationship, linear regression estimates of the parameters rely on the proposition that any departures in the plant data from Eq. 1, which cannot be directly observed, are randomly distributed within the population. This implies that the actual relationship includes a random error term ε that follows a normal (bell-shaped) distribution. For simplicity, we assume that the function $f(\,)$ is linear in the parameters, but allow for non-linear transformations of the variables. In this case, production, and capacity enter the equation in log form, as does the energy variable.

$$ln(E) = f(ln(Y), X; \beta) + \varepsilon \qquad (2)$$

$$\boldsymbol{ln(E) = a + \sum_{i=1}^{n} b_i\, ln(y_i) + \sum_{i=1}^{m} c_i\, X_i + \varepsilon} \qquad (3)$$

This means that ε can be interpreted as percentage deviations in energy, rather than absolute. This has implications for the model results since we now think of the distributional assumptions in terms of percent, rather than absolute level. In either case of a linear or log-linear functional form, standard measures of statistical significance provide a test for whether or not to include a particular characteristic. In other words, one can test if two different plant characteristics have different energy implications, in a statistically identifiable way.

Energy performance score (EPS)

Assuming we are using a model that has been estimated in one of the case studies in the out-of-sample context described above and we have data for a plant in a year different from the study data year, we can compute the difference between the actual energy use and the predicted average energy use from equation (3).

$$\boldsymbol{ln(E) - \left(a + \sum_{i=1}^{n} b_i\, \mathbf{ln}(y_i) + \sum_{i=1}^{m} c_i\, X_i\right) = \hat{e}} \qquad (4)$$

For the models using ordinary least square (OLS), we have also estimated the variance of the error term of equation (1), and we can compute the probability that the difference between actual energy use and predicted average energy use is no greater than this computed difference under the assumption that $\boldsymbol{\varepsilon}$ is normally distributed with zero mean and variance, σ^2.

$$\mathbf{Pr}(\boldsymbol{\varepsilon} \geq \hat{\boldsymbol{e}}) \qquad (5)$$

This probability is the Energy Performance Score (EPS) and is the percentile ranking of the energy efficiency of the plant. Since this ranking is based on the distribution of inefficiency for the entire industry, but normalized to the specific systematic factors of the given plant, this statistical model allows the user to answer the hypothetical but very practical question, "How does my plant compare to everyone else's in my industry, if all other plants were similar to mine?"

[1] Both ENERGY STAR and ISO 50001 use the term Energy Performance Indictor. Since ENERGY STAR began publically using the term first, ISO adopted the acronym "EnPI" to limit confusion.

EVOLUTION OF THE INTEGRATED STEEL EPI

The model evolved over a period of time, based on comments from industry reviewers and subsequent analyses. Opening conversations were used to produce a definition of an integrated steel mill as being a facility that is primarily engaged in producing steel products using a fully integrated process. Traditionally, this would mean a facility that converts iron ore into steel products and has a coke oven, blast furnace, basic oxygen furnace and rolling mills on site. For this analysis, plants may purchase coke or produce it on-site and final products include unfinished slabs, billets, as well as hot and cold rolled products. After examining the U.S. economic Census data, there were too few reported mills under the 331111 NAICS classification that met the above criteria to pass disclosure requirements, and therefore, the models developed were based on industry provided data.

The initial dataset was composed of nine plants from 2005-2009 that participated in the ENERGY STAR Steel Focus. After initial analysis, additional new baseline information was needed to accurately capture the energy usage of steel plants, and an additional three years of data was added to the model. Finally, the desire to add Canadian facility information meant additional data from existing plants was required to avoid disclosing the efficiency of the newly added plants. Since other companies had tested the previous versions of the model, any changes to their EPI scores would have been directly attributed to the data from the newly added plants. By including additional data for the existing plants, score changes can be attributed to a variety of model changes, avoiding the disclosure of confidential information. At the conclusion of the analysis, there were nine years' worth of data for most participating facilities (2005-2014). Using a wide range of panel data also helps to account for variability of production and shut downs across the facilities as long as shutdown times are of a similar length year to year.

Industry participants were given an opportunity to test and comment on each version of the model via meetings, quarterly conference calls, and personal communications. Companies were asked to input actual data for all of their plants and then to determine whether the results were consistent with any energy efficiency assessments that may have been made for these plants. The resulting comments improved the EPI. Different model suggestions by industry were considered including one that would compare plant component efficiencies (i.e., blast furnace or coke oven efficiency, etc.) and a cost based model that would report dollar savings of each plant compared to the average industry facility. Ultimately, the more broad, energy focused model was completed. The next sections discuss the background discussions and modeling approaches that were developed for the specific issues that were raised regarding intermediate products, finishing, oxygen and scrap use.

Imports and Export of Intermediate Products

From the outset of discussions on EPI development, the industry focus participants emphasized that, while easy to track, the energy use per ton of liquid iron produced did not take into account the diversity of plants' imports and exports of intermediate products, in particular cast steel slabs and hot mill bands. Both cast slabs and hot mill bands may be sent elsewhere for further processing. Conversely some plants may receive slabs as inputs to the hot mill or bands as inputs to the finish mill(s). The EPI analysis was structured to account for these differences. At each major stage of production, (blast furnace, the hot mill, and the finish mills) the amount of material that went into the next stage was accounted for. It was decided that a ratio of product volume from each stage relative to total production of cast steel slabs would be used. If this ratio was equal to one for all the process stages, it would represent a plant that processed all the iron made into final products. If any individual ratio was less than one, then that plant was exporting an intermediate product to be processed elsewhere. Conversely, a ratio greater than one would indicate that a plant was receiving semi-finished products for further processing. At any of these major stages, iron-making, steel-making, hot-mill, or finishing, imports or exports are possible. These are not the only production activities that occur at the plant, but they are the ones that the analysis was focused on for assessing the difference in energy use at different plants.

Finishing Processes

Steel products undergo a variety of finishing processes dependent on the final product. These processes vary from plant to plant and could vary in energy consumption and would need to be accounted for in the model. Types of finishing included batch annealing, hot dip galvanizing, continuous heat treating, tandem rolling, and plate rolling. Processing in the plate mill was deemed more similar to what occurs in the hot mill and therefore, data for both steel sent to the plate mill and the hot mill were combined. The initial approach to handle the other finishing processes was to include each one in the model separately. Early results proved to be inconsistent with industry expectations, and finishing was not going to be included in the model. However, industry testing revealed that plants performing in-house finishing were performing poorly in the draft model that ignored finishing entirely. Finishing lines can be mutually exclusive, but need not be. To account for this, a finishing variable was included that accounted for all bands from the hot mill that were sent to the tandem mill (and subsequent additional processing) or were identified by the company as "sent for final finishing". This accounts for a variety of finishing processes and final products and can act as a broad variable to capture energy consumption from all finishing types.

Oxygen

Oxygen is blown into the basic oxygen furnace (BOF) to help remove carbon and refine ore from the blast furnace (BF) into molten steel. In our case we are focused on oxygen use in the blast furnace, as this may vary across plants while the oxygen in the BOF is less likely to differ. Oxygen's impact in the BF in the combustion process may impact purchased fuels. In addition, producing oxygen is an electric intensive process. Although on-site production of oxygen was determined to compose a small percentage of electricity, the amount of oxygen used to produce steel could still be a component of the overall efficiency of the plant. Initial estimates showed that it did have a significant impact on energy usage in steel production[2]. However, for some plants, oxygen was hard to track or record and there were many gaps in the data, especially in the earlier years of the dataset. Since oxygen use is ubiquitous in the production of steel, imputations were made to estimate oxygen usage for plants with missing observations. Originally, the industry average for total oxygen used was computed and filled in for missing values. Due to some extreme outliers in the data that skewed the mean, this value was not representative of the typical oxygen consumption. To correct for this, imputations were tied to the reported ratio of oxygen use to production of steel slabs. The plant specific mean of the ratio of oxygen use to tons of cast slabs was computed for years where oxygen data was available and then multiplied by the reported slab production values from each year for each plant. This imputation method was more representative of the different levels of oxygen use at different plants and provided statistically significant results.

Scrap Inputs

Scrap rates, i.e., adding steel scrap to the blast furnace, may also have an impact on increasing energy use since the energy implications of a ton a scrap added to the furnace would be different than for a similar ton of iron. Scrap steel used in production was treated similarly to oxygen for the analysis. An initial industry average was used that tended to overestimate scrap usage. Scrap is not an essential material in steel production although it is commonly used but is sometimes difficult to track in internal production statistics. Participating companies not reporting steel scrap were asked if the missing data corresponded to a lack of data tracking or that no scrap steel was consumed. After determining which values needed to be imputed, the same estimation used for oxygen was computed. In this case, the coefficient on scrap steel remained significant in its effect on energy consumption.

Waste Water Treatment

Comments from industry reviewers raised a concern of plants that have their own waste water treatment systems on site. Mills may use a municipal or other third party to treat waste water instead of operating on-site treatment facilities. After examination of discharge permits from the EPA to determine which facilities operated on-site water treatment plants, the number of plants was minimal so this was not included in the analysis. Additionally, plant managers were more concerned with the internal production differences between plants than extra process equipment not directly related to production.

Sinter Plants

Comments from industry reviewers raised a concern of some steel mills that have their own sinter plants on site, while others do not. The number of facilities in our data with on-site sinter was small. Rather than accounting for sinter production within the statistical analysis, the sub-metered energy use from the sinter plant was subtracted from the energy use for those facilities, effectively removing them from the definition of the "integrated steel mill".

ANALYSIS

The EPI benchmark study must define the production boundaries and energy accounting for the analysis. This section covers the boundaries for the analysis, the energy accounting, data provided by the industry, the final statistical estimates, and some example results.

[2] Initial estimates were based on dropping missing data points.

Boundaries

To define the boundaries of the steel industry, there needed to be a fence line set that would limit the differences of the existing facilities in terms of inputs and outputs (see Figure 2). As mentioned above, industry representatives were concerned that the intermediate stages of production and associated imports and exports[3] of those intermediate products, i.e., cast slabs and hot mill bands, would have a major impact on energy use. One way to account for this would be to model each process step [2]. Instead the EPI analysis treats the fence-line as a "black box," but uses the statistical analysis to account for the differences in production patterns on the total energy use of the plant.

For inputs, some facilities produce their own coke on site to be used in production while others purchase it from other sources. Coke imports, exports, and inventories were significantly different between plants making it difficult to standardize across the industry as a whole. To account for this, coke ovens are not considered as part of the plant and coke purchased or produced for coke ovens was removed from the facility energy profile. Coke charged to the blast furnace is considered an input to the total energy calculation. Energy used in the on-site coke ovens is subtracted from total energy use. However, coke oven gas is produced and some may be utilized throughout the rest of the production process as an energy input. Produced coke oven gas needed to be incorporated with total energy purchases to reflect the full energy profile of the facilities. The first approach was to include all generated coke oven gas as an input energy for the production process. After discussions with industry members, it was apparent that the transfer rate from the coke oven is far less than 100%, and some facilities even have the opportunity to sell excess coke oven gas to nearby to third parties. To account for this, adjustment factors were used for gas used in the coke oven, and coke oven transfers were excluded from the total energy use. The concept of "coke oven gas available to the steel plant" was applied. This would be equal to coke oven gas produced, less usage in the coke oven itself or transferred off-site. This means that "coke oven gas available" is the amount used in the steel operations, plus gas that is flared. Flared gas therefore would be included in the energy (in)efficiency measure.

For outputs, energy usage differs depending on what the final products shipped are, as there are differences in the level of finishing done at any given site. Due to the variety of products each plant makes that can vary over time, the specific finishing processes were not included in the model. Key production elements that affect energy usage were identified for inclusion in the model including liquid iron, slabs produced, hot mill tons (including plate mill tons), and the amount of finishing that was done on site.

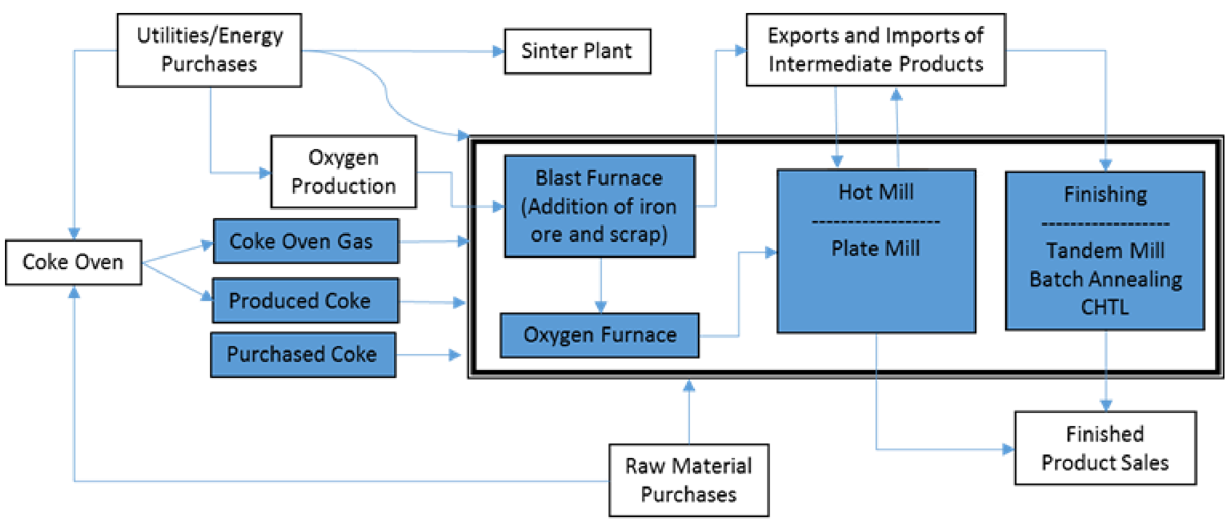


Figure 2: Stylized representation of the boundaries for the EPI analysis.

Energy accounting

Total source energy is used for the analysis. Total source energy is the energy purchased (or transferred) into the plant net of sales or transfers out. This includes any energy (electricity, steam, etc.) used in the coke oven or transferred/sold to third parties. Electricity is converted to Btu's by multiplying by a conversion factor that includes the U.S. average power plant and transmission losses thermal efficiency (3412 Btu/kWh * 3.14 loss factor = 10,714 Btu/kWh). This means that we do not directly

[3] The terms *imports* and *exports* are used to reflect transfers to and from the manufacturing plant, either as product sales or shipments to a facility owned by the company, not necessarily international sales.

account for on-site combined heat and power (CHP). If the CHP can displace purchased power at less than 10,714 Btu/kWh grid power, this would be an efficiency improvement. Coke charged to the blast furnace and coke oven gas available to the plant are included in other purchased energy, i.e., natural gas, boiler coal, etc.

Data

Three U.S. based and three Canadian based companies voluntarily provided data for 14 plants over a set time period (2005-2014) under a non-disclosure agreement with Duke University. Due to the evolving nature of the study, not all companies and plants provided for every year, resulting in an unbalanced panel. The total number of "plant-years" of data included in the final analysis was 106. Since no data collection should be viewed as perfect, the data underwent several rounds of quality assurance. Each company received a detailed spreadsheet that flagged large increases or decreases over time in energy and production. Those specific items were cross checked by the providing company and Duke University for accuracy. The means and standard deviations for selected data items are shown in Table 2. Units for production are in million (short) tons. Other variable units are shown in parenthesis. The means for slabs produced, liquid iron, and hot mill are all very similar, but it is the energy impact of the variation in these that the model seeks to explore. This variation is more clearly shown in Figures 2-5. These figures are the distribution of the raw data, represented as a kernel density plot[4]. Of particular interest is the wide range of energy intensity, i.e., total source energy per ton of cast steel slab. This can be thought of as the "raw data" measure of energy efficiency. However, this simple intensity is not a good performance indicator for efficiency.

Table 2: Summary Statistics (million short tons unless otherwise noted)

Variable	Mean	Standard Deviation
Total Energy (Trillion Btu)	56.40	28.06
Total Energy per ton (MMBtu/ton)	20.00	4.10
Slab Produced	2.84	1.25
Capacity	2.99	1.31
Liquid Iron	2.64	1.36
Scrap Steel	0.12	0.12
Hot Mill, Slabs Charged	3.02	1.70
Tandem – Finished	1.34	1.01
Oxygen (Trillion SCF)	11.25	6.14

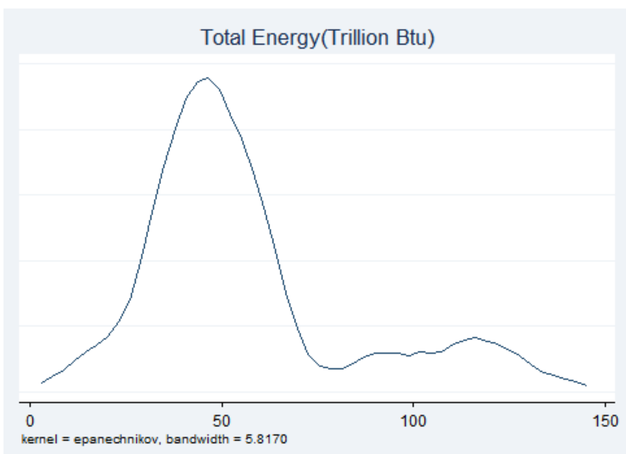


Figure 3: Distribution of Total Source Energy Consumption

[4] These plots can be thought of as a smoothed histogram. They are used to protect the confidentiality of the data.

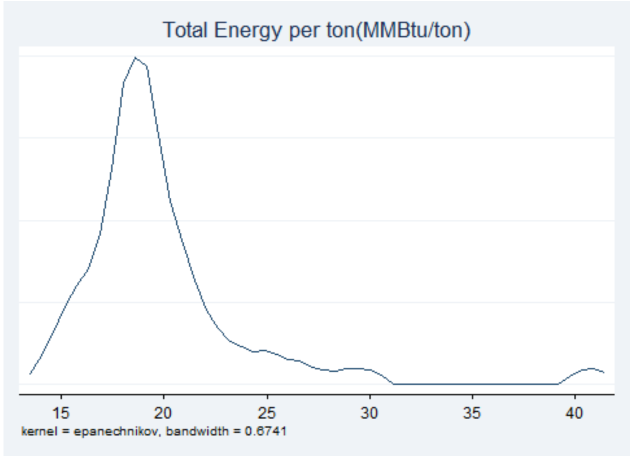


Figure 4: Distribution of Total Source Energy Consumption per Short Ton of Cast Steel

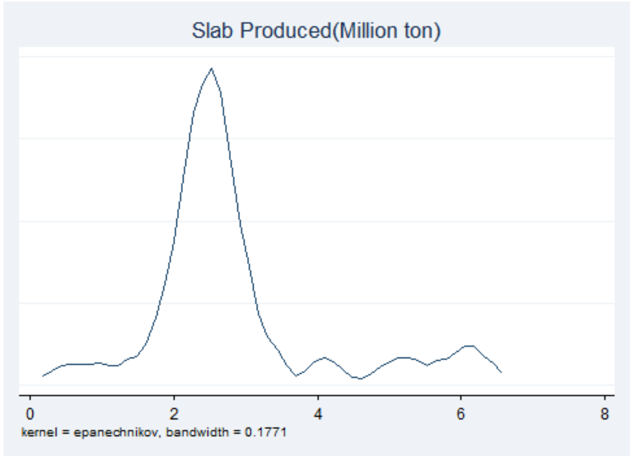


Figure 5: Distribution of Cast Steel Slabs

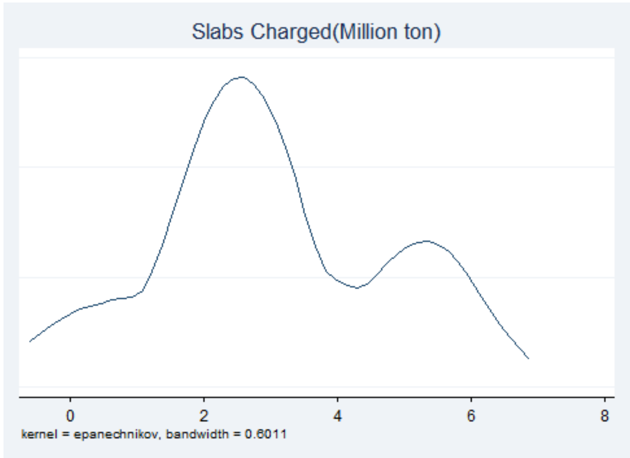


Figure 6: Distribution of Slabs charged to the Hot Mill

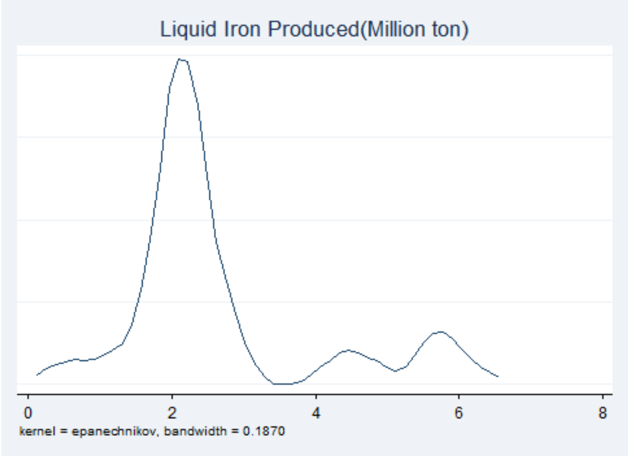


Figure 7: Distribution of Liquid Iron Produced

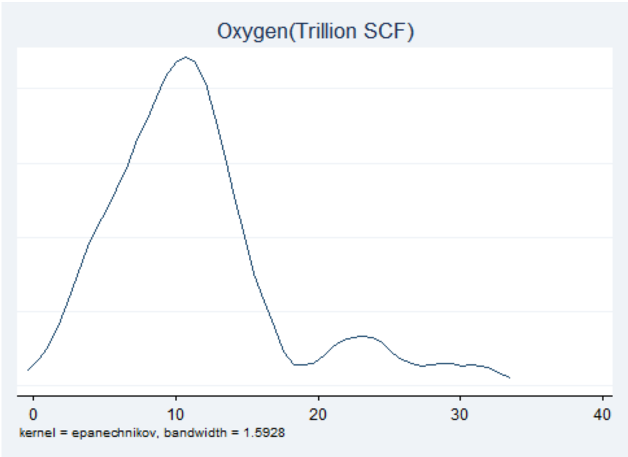


Figure 8: Distribution of Oxygen Consumed

Figure 9: Distribution of Scrap Steel Charged to the Furnace

Statistical estimates

The final version of equation (3) above used in the analysis is shown in equation (6) and the results are shown in table 3. The coefficients β_1 and β_2 are elasticities. This means that, since the coefficient β_2 is less than one, a 10% decrease in production, given a fixed capacity, would decrease energy by only 8.3%. However the sum of β_1 and β_2 is close to one, so a plant with 10% more capacity and production would basically be 10%. These estimates capture the fact that when production drops as it does during an economic recession, energy output ratios will rise. Coefficients β_{1-7} are harder to interpret directly. They are all positive, so as the production, relative to cast slab, of liquid iron, hot mill bands, scrap charged, or onsite finishing increases then the energy per ton of cast slabs will rise. This makes sense because all of these represent an increase in activity at the plant, relative to the "reference" of the amount of cast steel. An increase in oxygen also is associated with an increase in energy use.

$$\ln(energy) = \alpha + \beta_1 \ln(capacity) + \beta_2 \ln(cast\ slab\ production) + \beta_3 \left({liquid\ iron}/{cast\ slab}\right) + \beta_4 \left({slabs\ charged\ to\ hot\ mill}/{cast\ slab}\right) + \beta_5 \left({charged\ scrap}/{cast\ slab}\right) + \beta_6 \left({total\ onsite\ finished\ tons}/{cast\ slab}\right) + \beta_7 \left({oxygen\ use}/{cast\ slab}\right) + \beta_8 Year2009 + \varepsilon \qquad (6)$$

Table 3: Integrated Steel Mill Frontier Model Estimates

Variable	Coefficient	Standard Error	t-ratio
Log Capacity	0.2002	0.0374	5.36
Log Slab Production	0.8479	0.0272	31.17
Finished Production Ratio	0.0982	0.0303	3.24
Liquid Iron Production Ratio	0.5719	0.0536	10.64
Charged Scrap Production Ratio	0.3353	0.2695	1.24
Hot Mill Production Ratio	0.1362	0.0270	5.05
Oxygen Production Ratio	0.0208	0.0064	3.25
Year 2009	0.0464	0.0297	1.56
Constant	1.4088	0.3290	4.28
Error Distribution Parameters			
R – squared	0.984		
F(8, 97)	755.45		

Trend analysis

Since the data include multiple years, it is important to assess if there is a trend in the industry's energy's performance. To do so, a dummy variable for each year was added to the model to account for variations across years. No clear trend in energy performance was found. However, the steel industry was greatly affected by the recent recession, and production numbers fluctuated widely over the data period. Although these variables were not statistically significant, the size of the coefficients closely matched expectations. Lowest energy usage, and thereby production, occurred in 2009 in the height of the recession with the highest energy contribution coming from 2006, the earliest year in the sample. Concurrent with recent trends, the later years showed increasing energy contributions but still trailed those from 2006. After examining the effects from all years, the 2009 dummy variable was included in the final regression to account for the extreme impact on energy use in the recession. This, in addition to the capacity effects, is discussed above.

Stylized results

Returning to the raw data on energy intensity (Table 2 and Figure 4), we see that the range of performance is quite wide. The EPI analysis shows that this observation taken by itself is actually misleading. The blue line in Figure 10 takes the data from Figure 3 and transforms it into the distribution of plants that lie above or below the average energy intensity of 20 MMBtu/ton, represented as a percent difference. The full range of intensity difference exceeds 30% on either side. The red line representing the EPI analysis tells a very different story. Most of those differences come from differences that can be

accounted for in the analysis, more or less slabs, hot-mill bands, finishing or differences in capacity utilization. The range of actual efficiency, after these differences are accounted for is quite narrow. This is consistent with the results of a meta-analysis of EPI studies for other industries [11]. While less energy intensive sectors have a relatively wide range of efficiency, energy intensive sectors exhibit a much narrower range when other factors that influence plant energy use have been considered
.

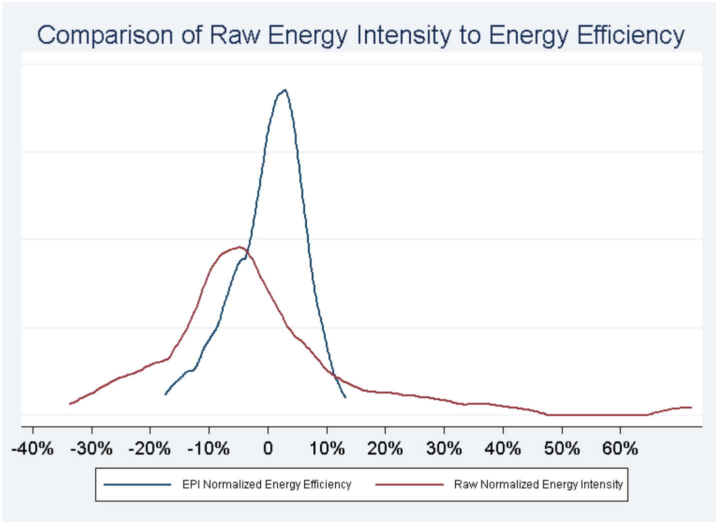
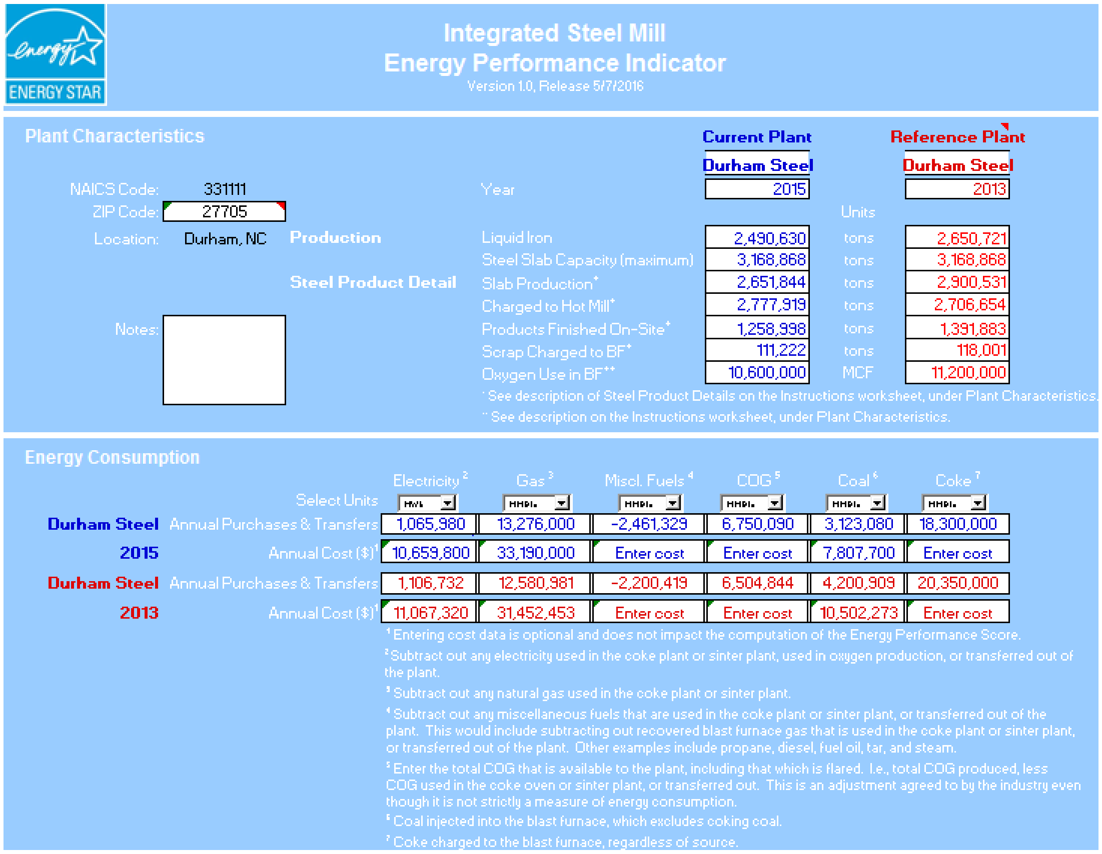


Figure 10: Comparing the Distribution of Intensity to Efficiency

USING THE EPI

The EPI analysis is incorporated into a simple spreadsheet for use by industry and others. It facilitates the out-of-sample analysis of more recent data or even hypothetical plant configurations. Figures 10 and 11 are screen-shots of the most recent draft of the spreadsheet provided to industry participants for review comment.



Integrated Steel Mill
Energy Performance Indicator
Version 1.0, Release 5/7/2016

Plant Characteristics

NAICS Code: 331111
ZIP Code: 27705
Location: Durham, NC
Notes:

		Current Plant Durham Steel	Units	Reference Plant Durham Steel
	Year	2015		2013
Production	Liquid Iron	2,490,630	tons	2,650,721
	Steel Slab Capacity (maximum)	3,168,868	tons	3,168,868
Steel Product Detail	Slab Production*	2,651,844	tons	2,900,531
	Charged to Hot Mill*	2,777,919	tons	2,706,654
	Products Finished On-Site*	1,258,998	tons	1,391,883
	Scrap Charged to BF*	111,222	tons	118,001
	Oxygen Use in BF**	10,600,000	MCF	11,200,000

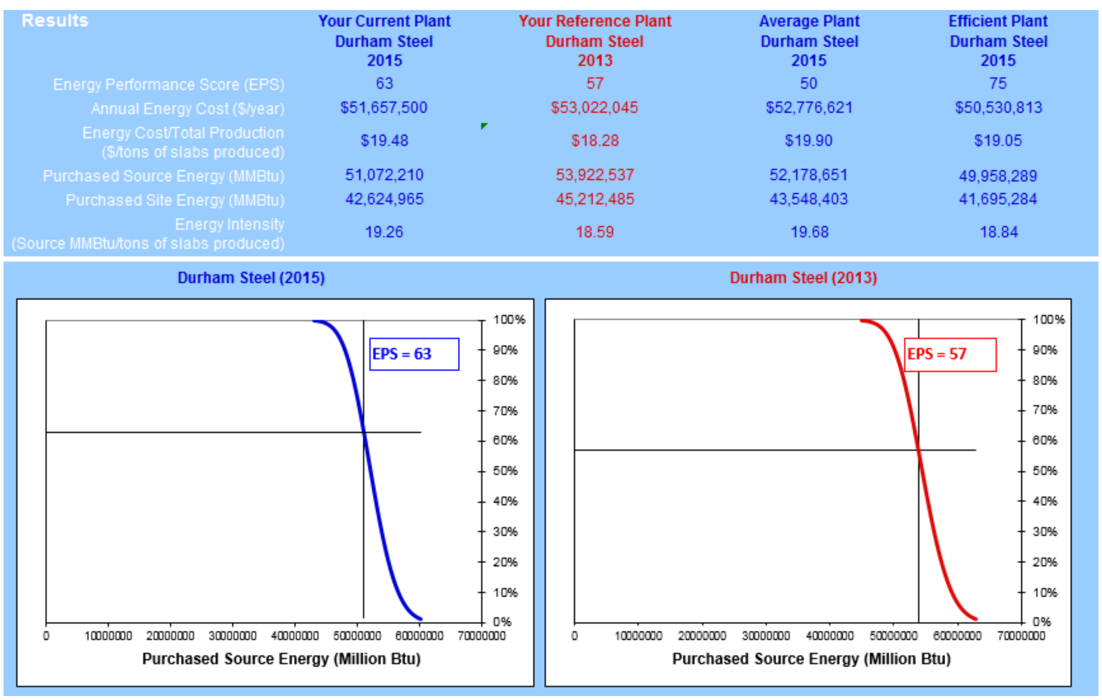
* See description of Steel Product Details on the Instructions worksheet, under Plant Characteristics.
** See description on the Instructions worksheet, under Plant Characteristics.

Energy Consumption

		Electricity [2]	Gas [3]	Miscl. Fuels [4]	COG [5]	Coal [6]	Coke [7]
	Select Units	MWh	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu
Durham Steel	Annual Purchases & Transfers	1,065,980	13,276,000	-2,461,329	6,750,090	3,123,080	18,300,000
2015	Annual Cost ($)[1]	10,659,800	33,190,000	Enter cost	Enter cost	7,807,700	Enter cost
Durham Steel	Annual Purchases & Transfers	1,106,732	12,580,981	-2,200,419	6,504,844	4,200,909	20,350,000
2013	Annual Cost ($)[1]	11,067,320	31,452,453	Enter cost	Enter cost	10,502,273	Enter cost

[1] Entering cost data is optional and does not impact the computation of the Energy Performance Score.
[2] Subtract out any electricity used in the coke plant or sinter plant, used in oxygen production, or transferred out of the plant.
[3] Subtract out any natural gas used in the coke plant or sinter plant.
[4] Subtract out any miscellaneous fuels that are used in the coke plant or sinter plant, or transferred out of the plant. This would include subtracting out recovered blast furnace gas that is used in the coke plant or sinter plant, or transferred out of the plant. Other examples include propane, diesel, fuel oil, tar, and steam.
[5] Enter the total COG that is available to the plant, including that which is flared. I.e., total COG produced, less COG used in the coke oven or sinter plant, or transferred out. This is an adjustment agreed to by the industry even though it is not strictly a measure of energy consumption.
[6] Coal injected into the blast furnace, which excludes coking coal.
[7] Coke charged to the blast furnace, regardless of source.

Figure 10. Input section to EPI Spreadsheet



Results	Your Current Plant Durham Steel 2015	Your Reference Plant Durham Steel 2013	Average Plant Durham Steel 2015	Efficient Plant Durham Steel 2015
Energy Performance Score (EPS)	63	57	50	75
Annual Energy Cost ($/year)	$51,657,500	$53,022,045	$52,776,621	$50,530,813
Energy Cost/Total Production ($/tons of slabs produced)	$19.48	$18.28	$19.90	$19.05
Purchased Source Energy (MMBtu)	51,072,210	53,922,537	52,178,651	49,958,289
Purchased Site Energy (MMBtu)	42,624,965	45,212,485	43,548,403	41,695,284
Energy Intensity (Source MMBtu/tons of slabs produced)	19.26	18.59	19.68	18.84

Figure 11. Output Section to EPI Spreadsheet

CONCLUSIONS

This paper provides an overview and the most recent results of a study to benchmark energy use in the integrated steel industry. It was undertaken by EPA to provide an energy management tool to industry and is the first EPI to incorporate data from both U.S. and Canadian plants. Based on input from industry, it focused on defining clear boundaries for the analysis and measured the energy impact of differences in the imports and exports of intermediate (semi-finished) steel from the mill. While the EPI statistical approach is not the only way to analyze energy in manufacturing, it provides important insights without resorting to detailed modeling of individual process steps and corresponding sub-metered energy data. The analysis clearly demonstrates that energy per ton of steel is an inadequate measure of energy efficiency and that plant specific factors have a large impact on energy use that should not be misconstrued as inefficiency.

ACKNOWLEDGMENTS

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