A Process-Step Benchmarking Approach to Energy Use at Industrial Facilities: Examples from the Iron and Steel and Cement Industries

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ABSTRACT

This paper looks at the use of benchmarking approaches to evaluating industrial energy use. Benchmarks have been used for comparing industrial facilities or entire sectors, or for making temporal comparisons. We outline a 'process-step approach' to benchmarking energy-intensive industries, which accounts for the process differences between industrial facilities or sectors. We then illustrate the approach using the cement and the iron and steel industries, and construct an example using data from the Brazilian iron and steel industry.

Introduction

Benchmarking can be a useful tool for understanding energy consumption patterns in an industrial sector and for designing policy to improve energy efficiency. Energy benchmarking for industry is a process in which the energy performance of an individual plant or an entire sector of similar plants is compared against a common metric that represents 'standard' or 'optimal' performance. It may also entail comparing the energy performance of a number of plants against each other.

Because benchmark evaluation tools are used for comparison across a number of plants or sectors, there are two important characteristics they should have. First, because they are applied to plants or sectors of different sizes and outputs, the metric used should be irrespective of plant size. This is accomplished by using the concept of energy intensity, which measured energy use *per unit of output*. However, deciding how to measure units of output is not always clear.[1] Second, the tool should be applicable to a wide range of facilities (in order to increase the robustness of the analysis) and so should be able to compensate for differences in production at similar facilities.

In designing an evaluation tool that compensates for production differences, it is necessary to take a look inside the production processes and account for the various steps used. Each of the examples we look at in the next section accounts for these steps in a similar way. In this paper we look at energy benchmarking for cement production and for iron and steel production, following an approach we call process-step benchmarking. In this approach, the key process steps are identified and a benchmark performance is assigned to each step. The performance of a plant is then compared incorporating information about how each step is used by the plant. In section 3 the process-step approach is explained more

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[1] For consistency, physical measures of output (i.e. tonnes of steel or paper) are preferable, but even these may include important differences, such as different steel products or different grades of paper. Economic measures of output are much more problematic, since product prices and value added can change significantly over time. This issue has been discussed in a DOE study (EIA, 1995)

thoroughly. Sections 4 and 5 describe the application of the approach to cement and to iron and steel production.

Existing Industrial Benchmarking Programs

Industrial benchmarking has been used primarily in three contexts. The first context is to evaluate an entire industrial sector, such as iron and steel, aluminum, cement, etc. This evaluation is used to answer the following questions: How well is this sector performing compared to how it would perform using the best available technologies? How well is it performing compared to the same sector in other countries? Has the sector been improving over time? The answers to these questions depend not just on state-of-the-art performance in the sector, but also the adoption of efficient technology throughout the sector.

The second context for benchmarking is the comparison of individual plants within a sector. A benchmark-type indicator is calculated for all the facilities within a sector so that they can be compared on even terms. This evaluation can answer the following questions: What is the state-of-the-art performance in this given sector? How does my plant compare against the state-of-the-art? How does it compare against the majority of other plants in the sector? In developing benchmarks at the level of individual plants, the issue of proprietary data becomes important. Individual companies are very reluctant to disclose information about their production processes, particularly if it will be released to their competitors. It is important that the indicators developed are general enough not to reveal any proprietary information and that a credible system is established that encourages plants to trust the process.

A third context for industrial energy benchmarking that has been seen widely in recent years is for large companies to set themselves energy efficiency goals by using benchmarks. Companies use this approach to set targets for reducing energy use by certain percentages over given time frames. Companies do not need to divulge any proprietary information, since the benchmarking is done internally.

Below we look at examples of industrial benchmarking within each of these contexts.

Netherlands Industrial Sector Benchmarking

The Dutch government has been developing a benchmarking methodology for looking at industrial energy use in the country. Developing benchmarks helps in understanding industrial energy consumption patterns in order to assist in policy design. These benchmarks are be used to establish voluntary agreements with industry, in which energy-intensive industries agree to reduce energy consumption to avoid additional regulation.

The approach has been that Dutch industries should be among the best in the world. Although the level that qualifies as 'best' is subjective, the concept is to compare Dutch industrial performance to other countries. In constructing these comparisons, researchers at Utrecht University accounted for different manufacturing approaches within the same industry that influence energy consumption (Phylipsen et al 1998). These differences, which they called *structural indicators*, could be accounted for in their analysis to create fair comparisons across countries. Some structural indicators they identified were choice of inputs (iron ore vs. scrap metal in steel making), variety of outputs (various quality of paper in papermaking), and import/export of intermediate products (the import of alumina for aluminum production.)

The industrial sector of any country can be compared against how it would perform using 'best practice' technology, accounting for the structural indicators. This ratio of how a country performs compared to how it could be performing can then be compared across countries.

Solomon Associates Benchmarking of Hydrocarbon Industries

Solomon Associates has offered benchmarking capabilities to hydrocarbon industries (refineries and chemical plants) for the past two decades. Their benchmarking tools cover many areas of production, including energy, which is the largest operating expense at many of these plants. They benchmark energy efficiency using a metric they call the Energy Intensity Index (EII) (Birchfield, 2000). In this approach, standard energy consumption factors are developed for each process unit in the hydrocarbon industry. For each facility, the throughput of materials at each unit is multiplied by the consumption factor, and these values are summed across all units to give a standard energy consumption value for the plant. Actual plant energy use is divided by this value to yield a percentage called the EII.

Solomon promotes its benchmarking tool as a source of information and as an incentive for process improvements. Their indices can, without revealing proprietary information, provide information on the state-of-the-art performance in an industry and tell an individual plant how it compares to other plants and to its own past performance. Knowledge that more efficient plants exist in an industry and the drive for process improvements and cost savings can drive gains in energy efficiency.

Company-Wide Energy Benchmarking

Some of the companies that have been using benchmarking approaches to set energy efficiency goals include DuPont, Dow, Royal Dutch Shell, BASF, and Chevron (Sun and Williamson, 1999). DuPont formed a Corporate Energy Leadership Team to bring attention to the issue of energy utilization. They set a goal to reduce energy intensity by 15% over the decade of the 1990's,[2] and they defined energy intensity as the energy consumed per unit of production, BTU/pound (Stewart, 1998).

In setting these targets, companies need to recognize that improvements in energy intensity come from two sources. One is improvements in energy efficiency – such that making the same products requires less energy – and one is structural changes, or changes in the profile of products that the company makes. Companies should distinguish between these two changes when setting targets so that their results are more meaningful. DuPont does report their energy savings on a global basis, so their improvements would not be a result of shifting energy-intensive processes to different countries.

[2] Dupont claims to have attained a 10% reduction in energy intensity on a global basis in the period 1990 to 1996.

The Process-Step Approach to Benchmarking

One of the major critiques of using a benchmark to evaluate industrial projects is that there is a rarely a homogenous output to use as the basis for measuring the intensity of energy use (Lazarus et al). In electricity generation, it is common to think of energy intensity in terms of energy use per kilowatt-hour of electricity generated. There is basically one output commodity in electricity generation, so this metric makes sense. For industrial manufacturing, output is generally much more heterogeneous. Some commodities appear to be fairly homogenous, such as steel, but a close look shows that steel output includes diverse products such as ingots, slabs, wire, and sheets, and the processes used can vary. For example, steel can be made starting with iron ore and coking coal, or can be made from recycled steel. Each of these differences translates into different energy requirements.

In the process step approach, the key energy-consuming steps for a manufacturing process are identified, and a facility is evaluated according to how well it performed at each of these key steps. If it is designed well, a process step evaluation tool can be used to compare a number of different facilities, even if their production methods and outputs vary. There are four key steps to setting up the process-step approach:

Step 1: Understand the Industrial Processes. The process step approach begins with an understanding of the production processes used in an industry. Often, there are a number of pathways that lead to the production of the one central product – such as liquid steel in the steel industry, or clinker in the cement industry. The production of this product encompasses the most energy-intensive production steps. There are then more pathways that lead from the central intermediate product to a number of final products – such as a wide range of steel products or various grades of cement. An understanding of the production pathways and key products is needed to correctly set up a benchmarking system.

Step 2: Set the Boundaries of the Analysis. After the key process steps are understood, a decision is required about which process steps are included in the analysis for an industry and which will be outside the analysis boundary. This decision is somewhat subjective, but is based on a combination of factors. The most energy-intensive steps should always be included, and steps with lower energy-intensity can be excluded, particularly if the data required for accurate evaluation are difficult to acquire. It is important that all potentially substitutable steps fall on the same side of the analysis boundary, whether that is inside of outside of the analysis. Setting up boundaries like this helps to make sure that all projects are evaluated fairly, and also helps to limit the data requirements by focusing the analysis as much as possible. Each of these steps must have some sort of measurable physical throughput that can be used as the basis of an intensity measure.

Step 3: Define the Benchmark Energy Categories. Once the process steps that will be used in the analysis have been set, there remains a decision about how to treat the benchmark categories. There are a few factors that are considered at this point. For example, is it necessary to include all of the energy sources in the analysis, or can focusing on the main energy sources help to simplify the analysis while still capturing the important information? Also, special consideration is needed for secondary energy carriers, including electricity and steam, to determine the primary energy savings associated with saving one unit of each of these.

Step 4: Determine Values for the Benchmarks. The final step is to establish benchmark intensities for each process step. There are two major approaches to determining the benchmark values. The first approach is to compile performance information from existing plants or plants that are under construction and to base the benchmark value on this data. The benchmark might be set as the average performance weighted by output, or it might be set to the top 10 or 25 percent of performance. A more sophisticated approach would be to estimate a trend in the data to look for improving performance that would indicate how future plants would be expected to perform. In practice, existing data are often not complete enough to do a thorough analysis of this sort. In any approach that determines a benchmark from a set of existing plants, there needs to be a decision about which plants are included when making the evaluation. Some parameter might be set, such as all plants built in the past ten years, or the most recent 10 plants built, to define which plants belong in the evaluation set.

The second major approach for determining benchmark values is to use data that represents 'best practice' performance, which could be derived from either observations at highly efficient plants or from scholarly publications that study the industry. This approach is much less data intensive than basing the benchmark of a set of existing plants, but these 'best practice' values may not be good indicator of the types of projects going on in individual countries.

Process-Step Benchmarking in the Cement Industry

Cement production is an energy-intensive process in which a combination of raw materials is chemically altered through intense heat to form a compound with binding properties. Raw materials, including limestone, chalk, and clay, are mined or quarried, usually at a site close to the cement mill. These materials are then ground to a fine powder in the proper proportions needed for the cement. These can be ground as a dry mixture or combined with water to form a slurry. The addition of water at this stage has important implications for the production process and for the energy demands during production. Production is often categorized as dry process and wet process. Additionally, equipment can be added to remove some water from the slurry after grinding; the process is then called semi-wet or semi-dry.

This mixture of raw materials enters the clinker production stage. During this stage the mixture is passed through a kiln (and possibly a preheater system) and exposed to increasingly intense heat, up to 1400 degrees Celcius. This process drives off all moisture, dissociates carbon dioxide from calcium carbonate, and transforms the raw materials into new compounds. The output from this process, called clinker, must be cooled rapidly to prevent further chemical changes. Finally the clinker is blended with certain additives and ground into a fine powder to make cement. Following this cement grinding step, the cement is bagged and transported for sale, or transported in bulk.

Figure 1 shows an overview of the key production steps in cement making. The box on this figure indicated where we choose to set a system boundary for this benchmarking analysis. The most energy-intensive stage of the process is clinker production, which accounts for up to 90 percent of the total energy use. The grinding of raw materials and of the cement mixture both are electricity-intensive steps and account for much of the remaining energy use in cement production.

For each of the process steps within the boundary, we focus on the major energy use at that step; for example, in clinker production we just include the combustion of fuel to generate the heat required, not the electricity used to rotate the kiln. Thereby, we are left with three benchmark categories:

- Electricity use for raw material preparation,
- Fossil fuel use for clinker production, and
- Electricity use for cement grinding (or finish grinding).

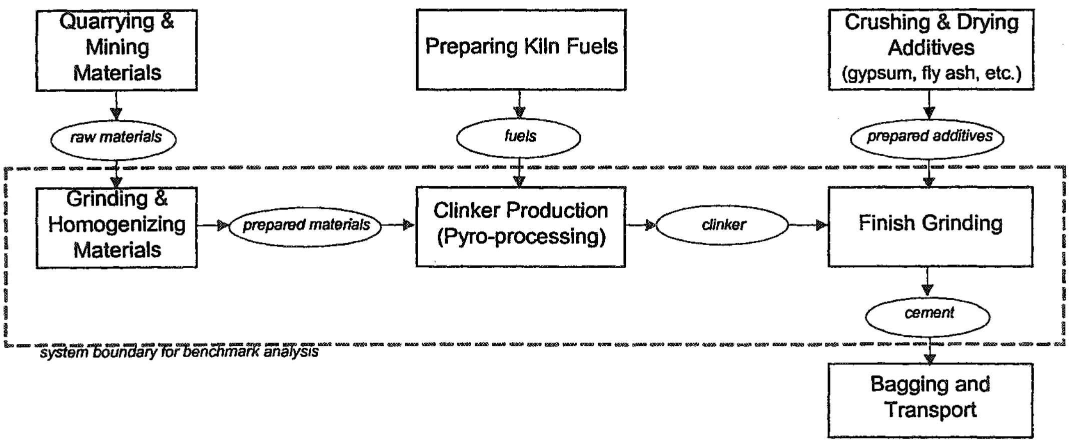

Figure 1. The Cement Production Process

Table 1 provides energy consumption values for the three cement-making process steps included in the system boundary. The first three rows of the table present "best practice" estimates of energy use in cement plants taken from two sources that survey the available technologies for cement manufacturing (Cembureau 1997, Conroy 1994). For raw material preparation and cement grinding, the main energy demand is electricity to power grinding mills, so these estimates are given in terms of kWh per tonne of material throughput. Energy requirements for cement grinding are roughly double those for raw material preparation because the cement is harder and need to be ground more finely than the raw materials. An important issue when considering "best practice" energy requirements for grinding is that energy use is related to the hardness of the raw materials and the additives included before cement grinding as well as the desired fineness of the finished product. These features can vary, so it is important to specify the fineness and composition of the product when discussing energy use. In this table we have included information on the fineness of the final product expressed in terms of cm^2 per gram of product.

Clinker production accounts for a majority of the energy use in the cement making process. Multi-stage preheaters and precalciners, which begin the clinker production process by eliminating water and bound carbon dioxide from the raw materials before they are sent to the kiln, are part of any "best practice" cement plant. Using these technologies energy use is around 3,000 kJ per kilogram of clinker produced. Wet process cement making uses much more energy, and even under "best practice" can consume up to 6,000 kJ per kilogram of clinker.

The second half of Table 1 provides examples from actual plant experience worldwide. Data on clinker production, the most energy-intensive step, are generally given, while grinding energy data are less commonly available. The four examples shown all use multi-stage preheaters and precalciners, and all show energy consumption around what is expected from the "best practice" information. In general, the energy use for grinding appears to be higher than the "best practice" estimates, although for cement grinding comparison is difficult because the final products vary.

Table 1. Energy Use Data for Three Cement Making Process Steps, "Best Practice" and Actual Performance

		Raw Material Preparation	Clinker Production		Cement Grinding	
	Plant	**Energy use (kWh/t raw meal)**	**Fuel Used**	**Energy Use (kJ/kg clinker)**	**Product Fineness (cm2/g)**	**Energy Use (kWh/t cement)**
Technical Publications	Cembureau – Dry	13-20	n/a	2900-3200	3500	24.5 – 36.5
	Cembureau – Wet	5-13	n/a	Up to 6000		
	Conroy's "Modern Plant Design"	10-11	Coal:	2990-3010	3600	25.0
Actual Plant Performance Data	Lampang, Thailand	21.4	Lignite:	3014	3300	41.76
	Bernburg, Germany	n/a	Lignite:	3008-3100	n/a	22.8
	Rajashree Cement, India	17-20	Coal:	2931 (*expected*)	3000	31.25
	Tepeaca, Mexico	n/a	Fuel oil:	3030	n/a	n/a

Sources: Cembureau, 1997, Conroy, 1994, Philipp et al., 1997, Seigert et al., 1998, Somani et al., 1997, Turley, 1995

Process Step Benchmarking in the Iron and Steel Industry

The manufacture of iron and steel involves a complex production process of many stages, some of which require very large amounts of energy. There are a number of alternative pathways through which steel can be produced (See Figure 2). One way is to begin with the basic raw material for steel: iron ore. After the ore is mined, it must be prepared for ironmaking through processes of sintering or pelletizing. Iron exists in an oxidized state in the ore; to produce the pure metal, the oxygen needs to be removed through a process called reduction. Reduction is most commonly done in a blast furnace using a carbon source called coke. Cokemaking usually occurs at the plant, using metallurgical coal as a feedstock. The iron ore material and carbon source then enter the smelting process, a method of ironmaking requiring very high temperatures (~1500 °C) and resulting in pure iron in a molten state. This molten iron then enters the steelmaking process, where it is treated with oxygen to remove carbon that remains in the iron from the reduction process. Scrap metal is also added at this stage to moderate the temperature of the steel, and additives can be introduced to form various alloys. The resulting liquid steel is then cast into ingots, strips, or other shapes. These shapes go through various rolling stages to create the final steel products.

An alternative pathway for steel production relies more heavily on the use of scrap metal. Scrap metal can be melted in a furnace that uses large amounts of electricity to bring the temperature of the metal to ~1900 C. The resulting molten materials can be treated to remove impurities, or other additives can be introduced to produce alloys. This electric arc furnace can also use a form of iron known as sponge iron or directly reduced iron (DRI) as a feed material. Sponge iron or DRI is produced when iron ore is directly reduced, usually using natural gas, at lower temperatures than in reduction with coke (~800 – 900 C).

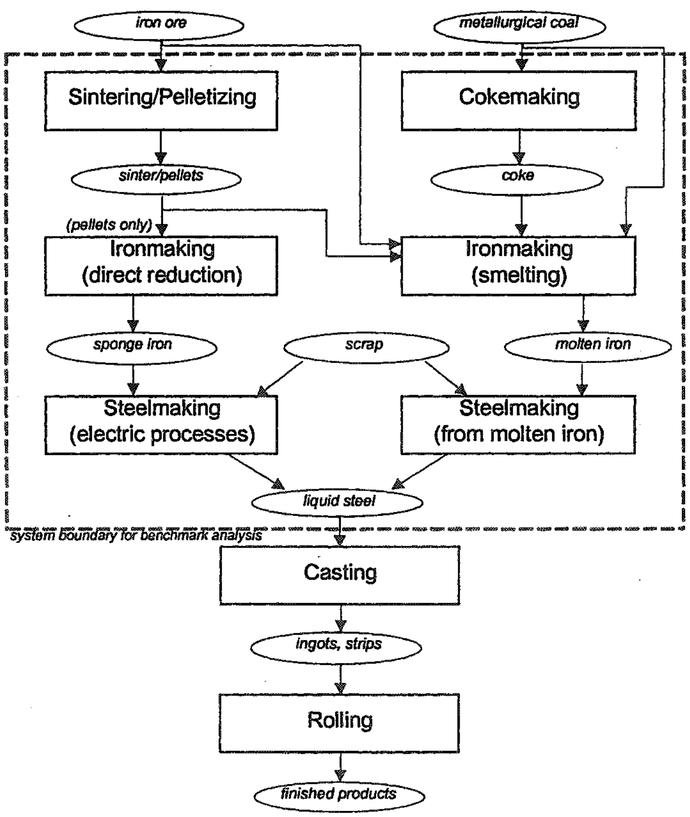

Figure 2. The Iron and Steel Production Process

As Figure 2 indicates, our benchmarking analysis draws a system boundary to include 6 production steps that include the preparation of materials, the making of iron, and the making of liquid steel (Ruth et al. 2001). For this paper we will focus on four of those stages to explain the benchmarking approach. These stages are part of the "integrated" steel making process: cokemaking, sintering, ironmaking through smelting, and steelmaking from molten iron.

Energy performance values for the four key integrated process steps are given in Table 2. These values are take from the International Iron and Steel Institute (IISI, 1998), which assessed the state of technology for the industry and established two energy performance levels: Eco-Tech and All-Tech. Eco-tech performance is based on the use of technologies and measures that would be economical for a plant to use. All-Tech includes technologies that may not be currently economical but lead to greater energy savings.

There is no difference between the Eco-Tech and All-Tech performance for steelmaking since it is already an exothermic (energy-releasing) process. It also appears that at the ironmaking stage, the more advanced "All-Tech" uses slightly more energy. In fact, what the summary data does not reveal is that the "All-Tech" performance includes an increase in gas or coal injection into the blast furnace, a practice which may increase the total energy use but lowers the amount of coke used. Less coke breeze is also used in the sintering step. Since less coke is needed, less coke is made, so there are energy savings at that stage. This illustrates that the benchmarking evaluation tool must account for energy savings is one stage that arise from changes that occur in another stage.

If the analytical approach looks at each process step separately and based only on its own level of throughput, the energy savings that arise from the interdependence of process stages would be missed. For the iron and steel industry we address that issues by calculating a 'coke balance'.[3] Since the IISI benchmarks at the ironmaking and sintering stages include a value for coke use, any savings in coke should lead to savings both in coke use and in the energy used to make coke. To calculate the coke balance, the amount of coke 'allowed' by the benchmark is calculated, then the amount produced and the net imports is subtracted to give the amount of coke production 'avoided'. This amount is multiplied by the cokemaking benchmarks to determine the energy saved.

Table 2. Energy Performance at Four Process Steps in Integrated Steelmaking

	"Eco-Tech" Benchmarks		"All-Tech" Performance	
	Fossil fuels	**Utilities**	**Fossil fuels**	**Utilities**
Cokemaking (per tonne of coke)	3.2 GJ	0.29 GJ steam 31 kWh elec	2.6 GJ	-0.85 GJ steam 31 kWh elec
Sintering (per tonne of sinter)	1.43 GJ	77 kWh elec	1.11 GJ	69 kWh elec
Ironmaking – Blast Furnace (per tonne of hot metal)	11.53 GJ	0.40 GJ steam 26 kWh elec 0.16 GJ O2	11.55 GJ	0.38 GJ steam 9 kWh elec 0.24 GJ O2
Steelmaking – Basic Oxygen Furnace (per tonne of liquid steel)	-0.58 GJ	-0.18 GJ steam 26 kWh elec, 0.42 GJ O2	-0.58 GJ	-0.18 GJ steam 26 kWh elec, 0.42 GJ O2

Example: Evaluating Brazilian Iron and Steel Plants

The approach described above can be tested using a dataset of integrated iron and steel plants operating in Brazil (ABM, 1999). Four plants were chosen for the evaluation – CST, CSN, Usiminas, and Cosipa – and they are compared against a benchmark based on the "Eco-Tech" performance from IISI.

Table 3 illustrates the comparison of these four facilities. Output among these plants ranges from 3.5 to 4.7 million tonnes per year and energy consumption ranges from 16.9 to 21.7 GJ/tonne[4]. The benchmarks for the plants vary also, because they make each of the four intermediate products in different proportions. CST makes the most sinter of all four

[3] In cement production, the amount of clinker used in finished cement (the clinker-to-cement ratio) illustrates the interdependence of steps in that industry. The authors have done a detailed analysis of how that relationship affects energy benchmarks (Ruth et al. 2000).

[4] This calculation is based on an assumption that electricity is generated at 33% efficiency and steam is generated at 88% efficiency. In actual iron and steel facilities, both steam and electricity are generated at the plant to meet some or all of the plant's requirements. The performance of these generators and boilers would ideally be included in a benchmark analysis, but we are limited by data for this analysis.

facilities, nearly twice as much as Usiminas, which explains why they have such different benchmark values. Of the four facilities, only CST shows a negative coke balance, meaning it is the only plant where less coke is used than is allowed by the benchmarks at sintering and ironmaking stages. These factors make CST the most efficient of the facilities examined here, in fact, it scores a benchmark value below 100%, indicating performs below the benchmark values set by the IISI publication.

Table 3. Energy Performance at 4 Brazilian Iron and Steel Plants.

Plant Name:	CST	CSN	Usiminas	Cosipa
Steel Output (tonne/year)	3,817,978	4,711,544	4,023,219	3,519,379
Energy Consumption (GJ/tonne)	16.90	18.69	17.99	21.11
Energy Benchmark (GJ/tonne)	17.43	15.52	14.68	15.84
Coke Balance (tonne coke/tonne steel)	-0.04	0.04	0.05	0.06
Benchmark Value (%)	96.0%	121.4%	123.8%	134.6%

This benchmarking approach also allows for comparison at the process step level. Figure 3 shows how the four Brazilian iron and steel plants perform at each process step compared to a benchmark based on IISI. The size of each bar represents how much energy was saved (or used in excess of the benchmark). Not only did CST perform better than the benchmark on a total basis, but also at the cokemaking, sintering, and ironmaking stages. This figure illustrates that the energy accounted for in the coke balance is small in comparison to savings or excesses at the process stages.

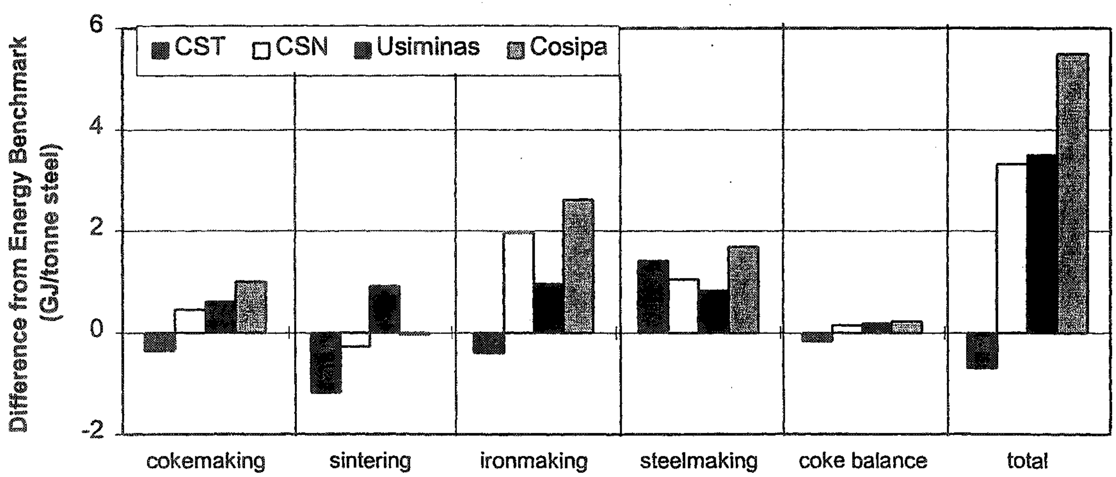

Figure 3. Energy Performance of 4 Brazilian Iron and Steel Plants at the Process Step Level, Relative to Benchmark Values

Discussion & Conclusions

The use of benchmarking has arisen in industry as an important tool for evaluating performance and making comparisons across plants, sectors, or time periods. Benchmarks for energy performance have become important policy tools for governments, incentive programs across sectors, and public relations tools for a company. As benchmarks become more commonly used in a variety of situations, it is important that benchmarking approaches follow some key guidelines to make comparisons fair and meaningful. Regular benchmarks over time provide additional information on the impact of, for example, operational changes and weather related variations (e.g. in power production).

Benchmarks should be set on the basis of energy intensity, preferably including physical measures of throughput as part of the metric, instead of economic measures. Since the plants or sectors being compared will be similar but not identical (or a single plant or sector may be changing over time), it is important to have an evaluation tool that compensated for these variations. The process-step approach described in this paper offers such an evaluation tool. For benchmarking to be meaningful, the production process used in an industry must be accounted for. A steelmaking plant that uses 50% recycled steel will have different energy requirements for one using 10% recycled steel. A country that imports large amounts of coke will have different energy use patterns from a country that produces all its coke domestically.

When benchmarks are meaningful, fair, and reliable, they can provide the basis for important changes in energy efficiency. Benchmarks for an entire sector can be used by governments to negotiate voluntary agreements with industries in that sector, whereby companies in that sector agree to energy efficiency targets suggested by the benchmarks. Within a sector, benchmarks can show how all companies or plants are performing, which gives individual plants a perspective on their performance and an incentive to improve. For these types of programs to be effective, a solid evaluation tool is needed to convince all participants of the equity of the process.

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