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A New Methodology for Calculating the Energy Performance of Manufacturing Facilities

Authors List

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Authors Bio

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A New Methodology for Calculating the Energy Performance of Manufacturing Facilities

Abstract

Total energy comparison (TEC), classic energy intensity (CEI), and linear regression models (LRM) are the three most common approaches used to track the energy performance of manufacturing facilities. TEC simply compares the total energy consumption from utility bills. TEC is rarely used because it does not consider the variation of any factors that may affect energy consumption. One step better, CEI considers the variation of production rates by using the ratio of annual total energy consumption over annual total production. However, CEI fundamentally assumes that energy consumption is zero if the production rate is zero. This is almost never true and can cause significant errors. Using linear regression models, LRM considers the impact of multiple variables and, therefore, most accurately tracks energy performance. Unfortunately, because of the lack of either required data or technical expertise, some facilities cannot create valid linear regression models. For these cases, CEI is the only option. The goal of this study is to develop a new methodology, modified energy intensity (MEI), which is more accurate than CEI, but requires much less data and is easier to implement than LRM. Using the underlying principle of LRM, this study first outlines the mathematical derivation of the equations for MEI, then explains them from an engineering perspective. Finally, the implementation of MEI is discussed.

Nomenclature

$\widehat{\ }$	Baseline year	E_P	Annual production energy
$\overline{\ }$	Analysis year	E_T	Annual total energy
$\%_B$	Percentage of base energy	EI	Energy intensity
$\%_P$	Percentage of production energy	LRM	Linear regression models
AY	Analysis year	MEI	Modified energy intensity
BE	Base energy	P	Annual total production
BY	Baseline year	S	Annual energy savings (%)
CEI	Classic energy intensity	SL	Slope of linear regression model
E_B	Annual base energy	TEC	Total energy comparison
E_M	Modeled annual energy using		

Introduction

The three most common approaches used to track the energy performance of manufacturing facilities are total energy comparison (TEC), classic energy intensity (CEI), and linear regression models (LRM).

TEC simply compares the annual total energy consumption obtained from utility bills of manufacturing facilities and does not consider the impact of the variation of any potentially relevant variables. By using identical time periods (e.g. over a full year, summer-to-summer), the effects of weather can be mitigated. The only data point needed for this approach is the annual total energy. Equation (1) shows the calculation of annual energy savings using TEC.

$$S = 1 - \frac{\overline{E_T}}{\widehat{E_T}} \qquad (1)$$

By rearranging Equation (1), the equation of constant energy savings lines of TEC can be derived to be Equation (2).

$$\overline{E_T} = (1 - S) \times \widehat{E_T} \tag{2}$$

The 0%, 10% and -10% energy savings lines of TEC are plotted in Figure 1. The annual energy savings obtained from TEC only depends on annual total energy and not on production rates or any other factors. When the annual total energy of analysis year is 10% less than that of baseline year, the annual energy savings is 10%.

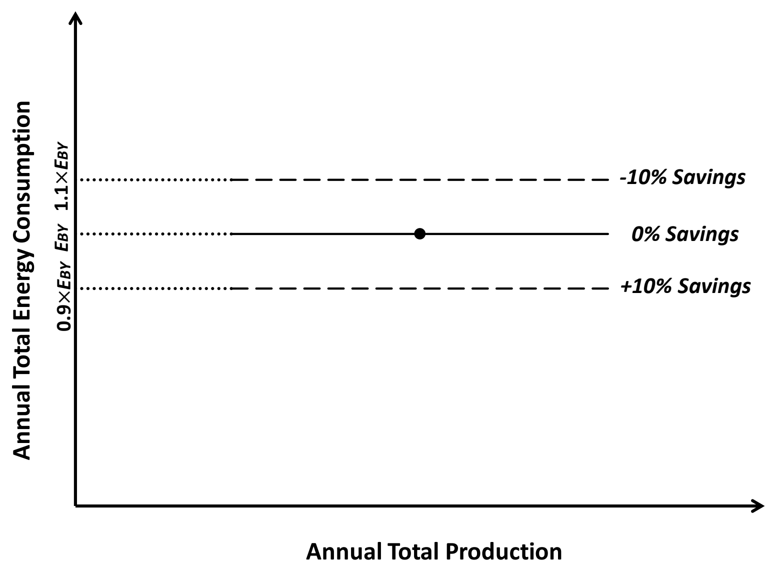

Figure 1 Constant energy savings lines of TEC

By incorporating the variation of production rate, CEI is an improvement over TEC. However, since the CEI approach utilizes the ratio of annual total energy over annual total production, the production rate is the only factor considered. Furthermore, CEI fundamentally assumes that all energy end-users perfectly load and unload with production rates and that when the production rate is zero, energy consumption is zero [1]. Because of technological and operational limitations, this assumption is rarely valid [2]. Compared with TEC, CEI requires one more data point: annual total production. Equation (3) shows the calculation of annual energy savings using CEI.

$$S = 1 - \frac{\overline{E_T}/\overline{P_T}}{\widehat{E_T}/\widehat{P_T}} = 1 - \frac{\overline{EI}}{\widehat{EI}} \tag{3}$$

By rearranging Equation (3), the equation of constant energy savings lines of CEI can be derived to be Equation (4).

$$\overline{E_T} = (1 - S) \times \frac{\widehat{E_T}}{\widehat{P_T}} \times \overline{P_T} \tag{4}$$

The 0%, 10% and -10% energy savings lines of CEI are plotted in Figure 2. The annual energy savings from CEI is a function of the ratio of annual total energy over annual total production, or the “energy intensity”. When the energy intensity of analysis year is 10% less than that of baseline year, the annual energy savings is 10%.

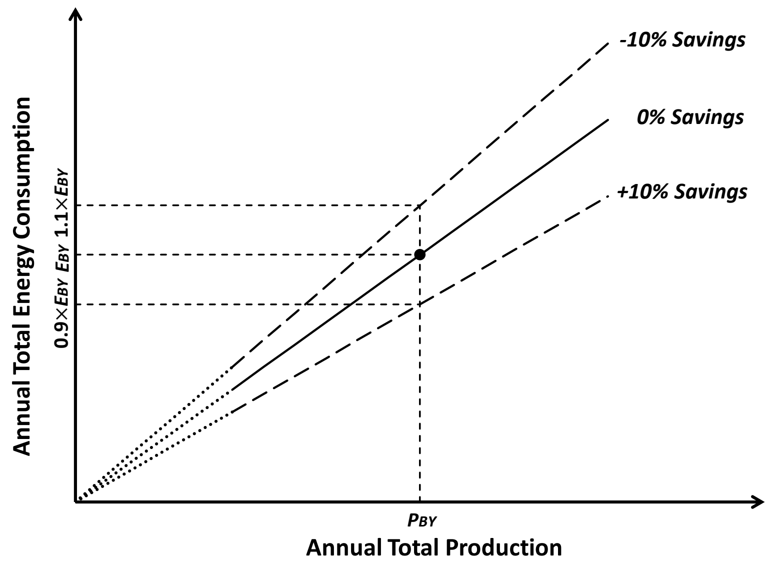

Figure 2 Constant energy savings lines of CEI

LRM is the most advanced and accurate method among these three discussed in this study. Using monthly or shorter time interval data, LRM develops a linear regression equation to describe the relationship between energy consumption and independent variables affecting energy consumption (e.g., production rates, heating degree days, cooling degree days, building square footage, and shifts). This equation is then used to normalize energy consumption, allowing for more accurate comparisons despite variation in relevant variables.

LRM has three approaches: forecast, backcast and chaining, based on which year is used to develop the model (the model year) [3]. Forecast uses the baseline year as the model year, backcast uses the analysis year, and chaining uses any year in between. The model year should be the year that produces an equation model that best explains the variance and is valid over all of the years of the analysis. Equation (5) shows the calculation of annual energy savings using LRM's forecast approach.

$$S = 1 - \frac{\overline{E_T}}{\widehat{E_{T,M}}} \tag{5}$$

When only the production rate is considered, by rearranging Equation (5), the equation of constant energy savings lines is derived to be Equation (6).

$$\overline{E_T} = (1 - S) \times SL_{BY} \times \overline{P_T} + (1 - S) \times BE_{BY} \tag{6}$$

When only production rates are considered, using Equation (6), the 0%, 10% and -10% energy savings lines of LRM are plotted in Figure 3. LRM essentially treats total energy consumption as the sum of base energy (the equation constant, independent of production rate) and production energy (production rate dependent). This is the fundamental reason why LRM is more accurate than CEI. LRM can consider more variables than production rates only, further increasing its accuracy over CEI.

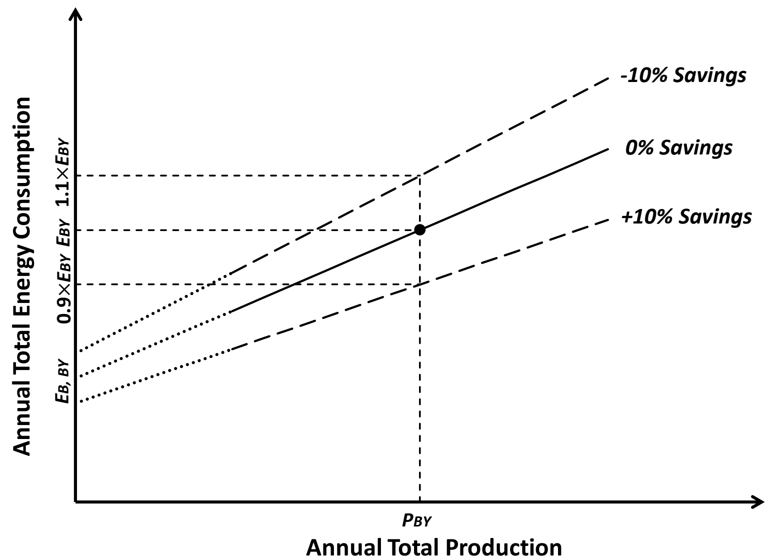

Figure 3 Constant energy savings lines of LRM

Figure 4 illustrates the resulting difference in annual energy savings between these three methods using a real set of monthly electricity usage data from a transportation equipment manufacturing facility. The overall higher production of analysis year leads to a false inflation of energy savings. The savings from LRM is only 2.8%, but the savings from CEI is 15.1%.

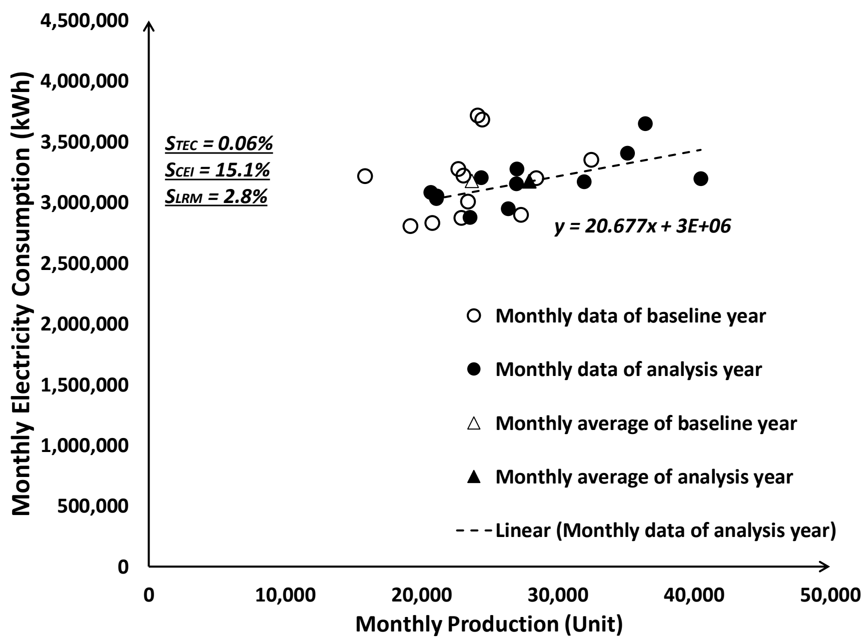

Figure 4 Energy savings calculated using TEC, CEI, and LRM

Because of LRM's significant accuracy advantage over the other two approaches, energy experts always recommend using LRM to calculate the energy savings of manufacturing facilities [1, 3, 4, 5]. Compared with TEC and CEI, LRM requires significantly more data points: at least 24 sets (monthly energy, production or other relevant variables) of data points to generate regression models. In addition, statistical and engineering technical expertise is required to create linear regression models and evaluate the models' validity. Unfortunately, some facilities lack either required data or technical resources to create valid linear regression models. For these cases, although CEI can cause significant errors, it is the only option. There are some other energy performance tracking methods that are derivations of standard LRM [6, 7], but they are not widely used because of the required technical expertise.

The goal of this study is to develop a new approach, modified energy intensity (MEI), to bridge the gap between CEI and LRM. Like CEI, MEI considers only production rates, but it will incorporate the concept of base energy, making it more accurate than CEI and easier to implement than LRM. Using the principle of LRM, this study first mathematically derives the equations for MEI, then will explain them from an engineering perspective, and finally, discuss the implementation of MEI.

Methodology Development

Mathematical Derivation

When only production rates are considered, LRM essentially treats total energy consumption as the sum of base energy and production energy. Any energy end-users can contribute to the base and production energy. Whether any energy consumption should be considered base or production energy depends if it is independent of production rate. For example, for most pharmaceutical manufacturing facilities, the energy consumption by HVAC system is base energy, since it is typically driven by requirements on air change rates, not by manufacturing rates. The energy consumption of lighting systems is another example of base energy as their operations are typically not affected by production rates.

Equation (7) shows the annual energy savings by using LRM's backcast approach.

$$S = 1 - \frac{\overline{E_{T,M}}}{\widehat{E_T}} \quad (7)$$

When only production rates are considered, Equation (7) is expanded as Equation (8).

$$S = 1 - \frac{\overline{E_B} + \frac{\overline{E_P}}{\overline{P}} \times \hat{P}}{\widehat{E_T}} \quad (8)$$

The base energy and production energy of analysis year can be expressed as the products of total energy times the percentage of base energy and production energy, respectively.

$$S = 1 - \frac{\overline{E_T} \times \overline{\%_B} + \frac{\overline{E_T} \times \overline{\%_P}}{\overline{P}} \times \hat{P}}{\widehat{E_T}} \quad (9)$$

As the sum of the percentages of base energy and production energy is one, Equation (9) can be rearranged to be Equation (10).

$$S = \overline{\%_B} + \overline{\%_P} - \frac{\overline{E_T}}{\widehat{E_T}} \times \%_B - \frac{\overline{EI}}{\widehat{EI}} \times \overline{\%_P} \quad (10)$$

Equation (10) can be rearranged to be Equation (11), which is the final equation for annual energy savings using MEI.

$$S = \overline{\%_B} \times \left(1 - \frac{\overline{E_T}}{\widehat{E_T}}\right) + \overline{\%_P} \times \left(1 - \frac{\overline{EI}}{\widehat{EI}}\right) \quad (11)$$

Savings from the MEI approach can also be viewed as the combination of the savings from TEC and CEI [Equation (12)].

$$S_{MEI} = \overline{\%_B} \times S_{TEC} + \overline{\%_P} \times S_{CEI} \tag{12}$$

By rearranging Equation (12), the equation of constant energy savings lines for MEI can be derived as Equation (13).

$$\overline{E_T} = \frac{1-S}{\frac{\overline{\%_B}}{\widehat{E_T}} + \frac{\widehat{P_T}(1-\overline{\%_B})}{\widehat{E_T} \times \overline{P_T}}} \tag{13}$$

Assuming the percentage of base energy of analysis year is 50%, the 0%, 10% and -10% energy savings lines for MEI are plotted in Figure 5 (using Equation [13]).

Unlike CEI, MEI does not assume the base energy to be zero; however, interestingly, when production approaches zero, the annual total energy of MEI is getting close to zero as well (Figure 5). This is because when the annual production rates are of very small values, the value of the second term in the denominator (representing the savings from CEI) will be very large, which causes annual total energy to approach zero. This typically happens only when production rates are out of the normal range and should not be of concern.

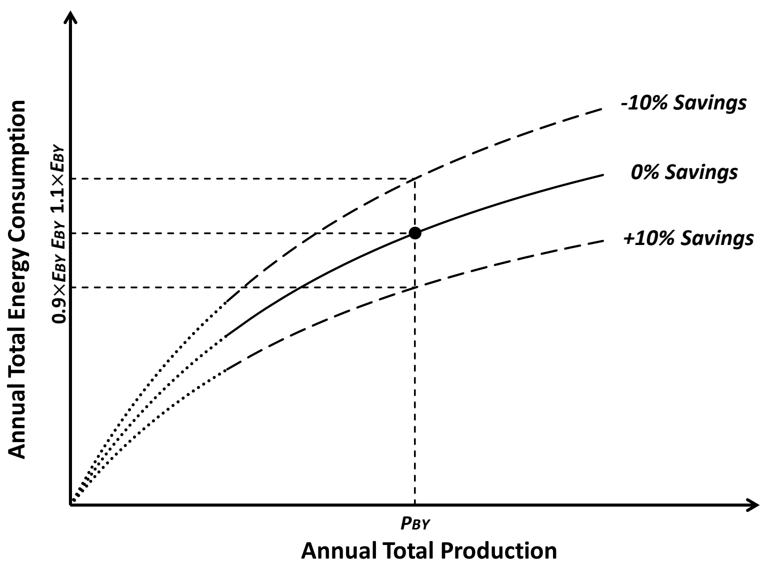

Figure 5 Constant energy savings lines of LRM

The 0% energy savings lines of these four methods are shown in Figure 6 which shows that the 0% energy savings line of MEI, like LRM, is a line between CEI and TEC. When assuming a higher percentage of base energy, the 0% energy savings line of MEI is closer to the line of TEC. On the other hand, when assuming a lower percentage of base energy, the 0% energy savings line of MEI is closer to the line of CEI.

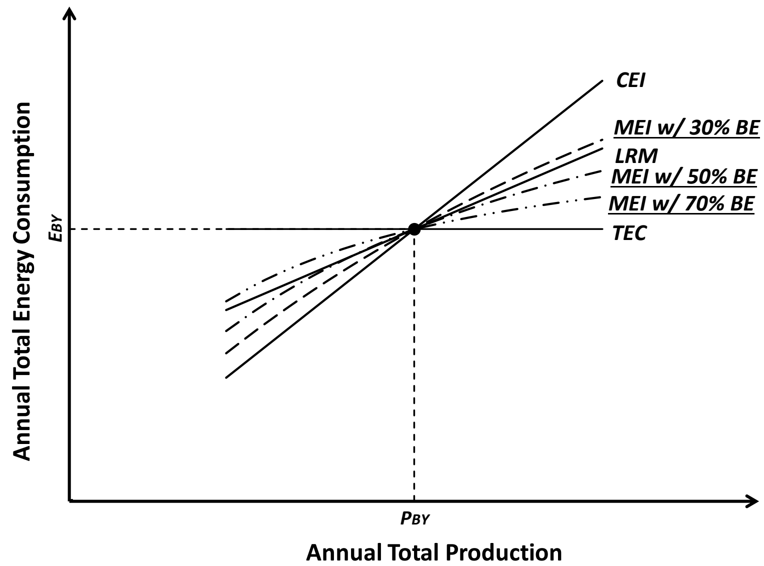

Figure 6 The 0% energy savings line comparison between TEC, CEI, LRM, and MEI

Returning to the example shown in Figure 4, the annual energy savings from MEI are 10.6%, 7.6%, 4.6%, and 3.1% when base energy percentages are 30%, 50%, 70% and 80%, respectively (Figure 7). In this example, the actual base energy is known to be about 82% and it can be seen that the savings assuming 80% base energy is the closest the savings calculated from LRM.

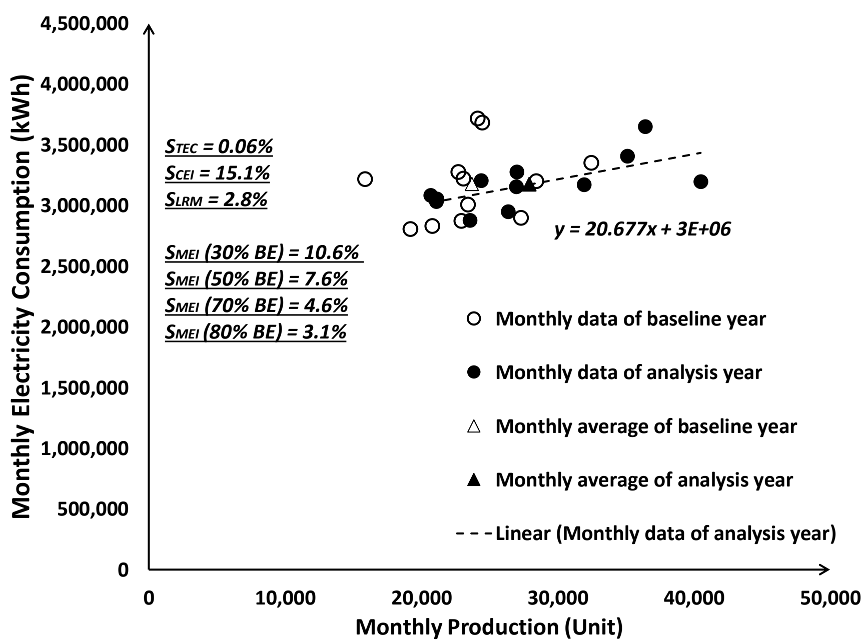

Figure 7 Energy savings comparison between LRM, CEI and MEI

Engineering Explanations

Let us assume that there are two fictitious plants. The operation of all energy end-users in Plant 1 is completely independent of the production rate and all energy consumption is base energy. In Plant 2, the operation and energy consumption of energy end-users are completely production dependent and the total energy consumption will be zero if production is zero.

Since the energy consumption of Plant 1 is production rate independent, the annual energy savings can be calculated using TEC approach [Equation (1)].

For Plant 2, since the energy end-users load and unload perfectly with production rates, the annual energy savings can be calculated using CEI approach [Equation (3)]

Most manufacturing plants can be viewed and treated as the combination of these two fictitious plants. The energy percentages of Plant 1 and Plant 2 can be different for various facilities and sectors. In simple terms, the annual energy savings of a manufacturing plant is the weighted average of the energy savings of Plant 1 and 2. The weighting factors are the energy consumption percentage of these two fictional plants.

$$S = \%_{Plant\ 1} \times S_{Plant\ 1} + \%_{Plant\ 2} \times S_{Plant\ 2} \quad (14)$$

By combining Equation (1) and (3), Equation (14) becomes the formula of MEI methodology [Equation (12)].

$$S_{MEI} = \overline{\%_B} \times S_{TEC} + \overline{\%_P} \times S_{CEI}$$

Implementation

Application Cases

If manufacturing facilities have neither monthly (or shorter time interval) operational data or technical resources to develop linear regression models, they can use MEI instead of CEI for a more accurate calculation of annual energy savings. If facilities do have the resources to develop linear regression models, but none of the developed models are statistically and engineeringly valid, they can use MEI for improved accuracy over CEI, as MEI allows them to better account for the base energy of the facilities.

If statistically and engineeringly valid regression models can be created, LRM is always recommended over MEI. Valid LRM models are always recommended since they do not have to make assumptions on base energy breakdowns and can account for other relevant variables (e.g., product types, weather, work shifts, and building square footage).

Percentage of Base Energy

As discussed previously, compared with CEI, MEI requires one more data point - the percentage of base energy. Facilities can calculate the percentage of base energy using sub-metered energy data; estimate based on equipment size, load and runtime; or estimate using the data from facilities with similar manufacturing processes. If these approaches are not feasible, facilities can estimate it based on the 2014 Manufacturing Energy Consumption Survey (MECS) data. Table 1 presents the typical percentage of base energy (including energy for facility lighting, HVAC, facility support, onsite transportation and other non-process use) for some sectors from MECS 2014.

Table 1: Typical base energy percentage for some manufacturing sectors [8]

Sector	Food	Beverage and tobacco products	Textile mills	Textile product mills
NAICS code	311	312	313	314

Electricity	19%	26%	26%	33%
Natural gas	9%	13%	8%	25%
Sector	**Apparel**	**Leather and allied products**	**Wood products**	**Paper**
NAICS code	315	316	321	322
Electricity	33%	NA	16%	10%
Natural gas	NA	NA	12%	5%
Sector	**Printing and related support**	**Petroleum and coal products**	**Chemicals**	**Plastic and rubber products**
NAICS code	323	324	325	326
Electricity	29%	7%	12%	23%
Natural gas	33%	1%	3%	23%
Sector	**Nonmetallic mineral products**	**Primary metal**	**Fabricated metal**	**Machinery**
NAICS code	327	331	332	333
Electricity	13%	12%	29%	40%
Natural gas	6%	7%	25%	44%
Sector	**Computer and electronic products**	**Electric equipment, appliances, components**	**Transportation equipment**	**Furniture and related products**
NAICS code	334	335	336	337
Electricity	41%	30%	38%	39%
Natural gas	36%	26%	38%	53%

Conclusions

A new methodology, MEI, was developed to calculate annual energy savings [Equation (13)] for manufacturing facilities. Like CEI, MEI considers only the variation of production rates; however, MEI does not assume the base energy (the energy consumption with zero production rates) to be zero. Therefore, MEI is significantly more accurate than CEI. LRM still remains the best and most accurate approach for energy performance tracking; however, when data availability, regression expertise and model validity is an issue, the MEI is the next best approach due to the simplicity and relative accuracy.

MEI was developed using the principle of LRM with only the variation of production rates considered. Compared with CEI, MEI requires an estimate of the percentage of the base energy for the analysis year. The percentage of base energy can be either calculated using sub-metered data; estimated based on equipment size, load and runtime; or estimated from plants with similar manufacturing processes. When neither of these two mentioned approaches are feasible, facilities can use the values in Table 1 for some manufacturing sectors.

Acknowledgments

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