Energy at Risk: Opportunities for Applying Benchmark Energy Factors in the Industrial Sector

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ABSTRACT

Benchmarking of energy performance plays a key role in advancing energy efficiency through enabling a useful comparison of relative performance and the identification of energy savings potential. Benchmarking tools employing mathematical models of energy use in the industrial sector have lagged behind those used in the commercial and institutional sectors given the complexity of industrial processes and variability of material and environmental conditions. Given the aforementioned variability and complexity, there can be an absence of a large population of comparable data required for a regression-based approach that would enable the normalization of material and environmental conditions, and thus allow for a useful comparison of energy performance at the process level. This problem is compounded by the reluctance of industrial firms to share data on industrial processes that is often considered proprietary. The authors highlight a novel method of benchmarking for the industrial sector that employs a theoretical model of the essential energy (minimum practical energy) required to produce a specific output while considering all material and environmental conditions that impact energy from a first principles approach. Actual energy consumption is divided by essential energy consumption to produce a benchmark energy factor (BEF) which allows for a normalized comparison of energy performance across operations, variations in products and over time. The BEF is a useful metric for assessing energy performance without the need for extensive site-specific measurements and complex process modeling of the actual energy baseline. The authors propose that this method could be used to develop a rating system for industrial processes similar to the U.S. Department of Energy's Energy Star Certification for Plants.

Benchmark Rating Systems

Industrial energy benchmarking is used by governments, energy utilities and industrial firms to compare the energy performance of sectors and plants within a given sector and over time. For governments, benchmarking is an essential tool for discerning trends in industrial energy use and developing policies to enhance energy efficiency and competitiveness. For industrial firms, benchmarking helps identify opportunities for energy efficiency improvements and facilitates target setting and monitoring of progress towards achieving targets. In plant-level benchmarking, a sector comparator benchmark is typically identified or calculated to enable a comparison with best available practices and technologies, highest performing facilities or the minimum essential energy required to produce a given output. Benchmarks are typically expressed in energy intensity to normalize for throughput differences between facilities. Comparator benchmarks are in some cases also adjusted for material and environmental conditions at each facility to allow for an equitable comparison of different facilities within each sector.

An adjusted comparator approach to benchmarking is useful because it also allows for the calculation of a simplified metric, or rating, indicating the normalized relative energy performance of similar facilities in a sector. One of the more prominent industrial benchmark rating systems is the U.S. Department of Energy's (DOE) ENERGY STAR Certification for Plants Program. The ENERGY STAR program develops "Energy Performance Indicators" (EPI) or benchmark ratings for twelve different industrial plant types, ranging from pulp and paper to cement manufactures. Plant personnel input twelve months of key operating data at the plant level to receive an energy performance score on a scale of 1 to 100. The ratings are calculated based on regression-based models of energy performance by typical product types in each sector derived from non-public industrial data collected by the U.S. Census Bureau. Those manufacturing plants that are within the top twenty-five percent of their industry are eligible to earn ENERGY STAR certification.

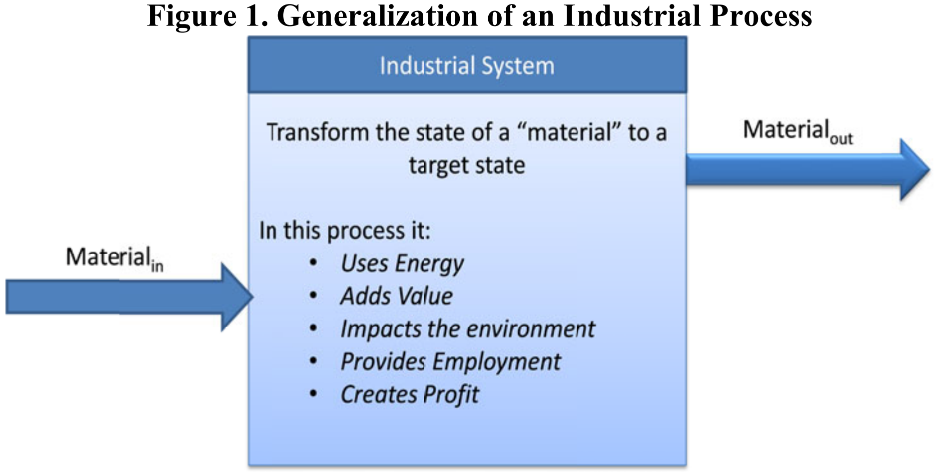
While the Energy Star Certification for Plants rating system has been effective at providing an overarching indicator of comparative energy performance, there is an opportunity to extend the benefits of this approach by applying it to industrial processes. Energy performance ratings for specific industrial processes would provide plant management and operators with a targeted indicator, or series of indicators, to enable deeper energy performance improvements.

Benchmark Energy Factor Methodology

The energy efficiency of industrial processes is often rated by comparing the energy use or a derived energy use intensity per throughput to a portfolio of existing processes that serve a similar, but not necessarily identical purpose. Such rating systems are often criticized for not reflecting the fact that the process under investigation deals with different or variable material inputs, and outputs that vary in quality.

Figure 1 shows a generalizing overview of an industrial process. Material of a certain quality entering the system is being transformed to a material/product that leaves the system. Typically, the produced material is of higher quality; value has been added. Within the process energy is always transferred from one state to another. It becomes apparent that the energy consumption for a given industrial process does not depend on the equipment and the system design alone, but also on non-controllable boundary conditions such as Material_{in} and Material_{out}.

Figure 1. Generalization of an Industrial Process



The authors propose a rating system to describe the energy-efficiency for any industrial process independent of a comparison with other processes while including adjustments due to varying material conditions. The Benchmark Energy Factor (BEF) compares the energy used by an industrial system or process (E_{used}) to the minimum energy required to accomplish the task at hand (E_{ideal}). A BEF value of 1.0 would be an ideal system with no avoidable losses.

$$BEF_{system} = \left.\frac{E_{used}}{E_{ideal}}\right|_{given\ input\ parameters}$$

Effectively, the BEF is a measure of the energy consumption by its productive energy and non-productive energy components. The productive energy is needed to manufacture the products and includes no potential for efficiency improvement. Enhancing the energy-efficiency of an industrial system/process means reducing the non-productive energy, or the energy at risk, thereby, bringing the BEF closer to unity. The ideal energy E_{ideal} represents the theoretical or minimum essential energy required to accomplish the task for the change in material conditions under a given environment. The ideal energy is the lowest energy possible and can be very accurately calculated by using established laws of physics and science. The difference between the actual energy used and ideal energy is defined as the energy-at-risk (E@R) using the equation:

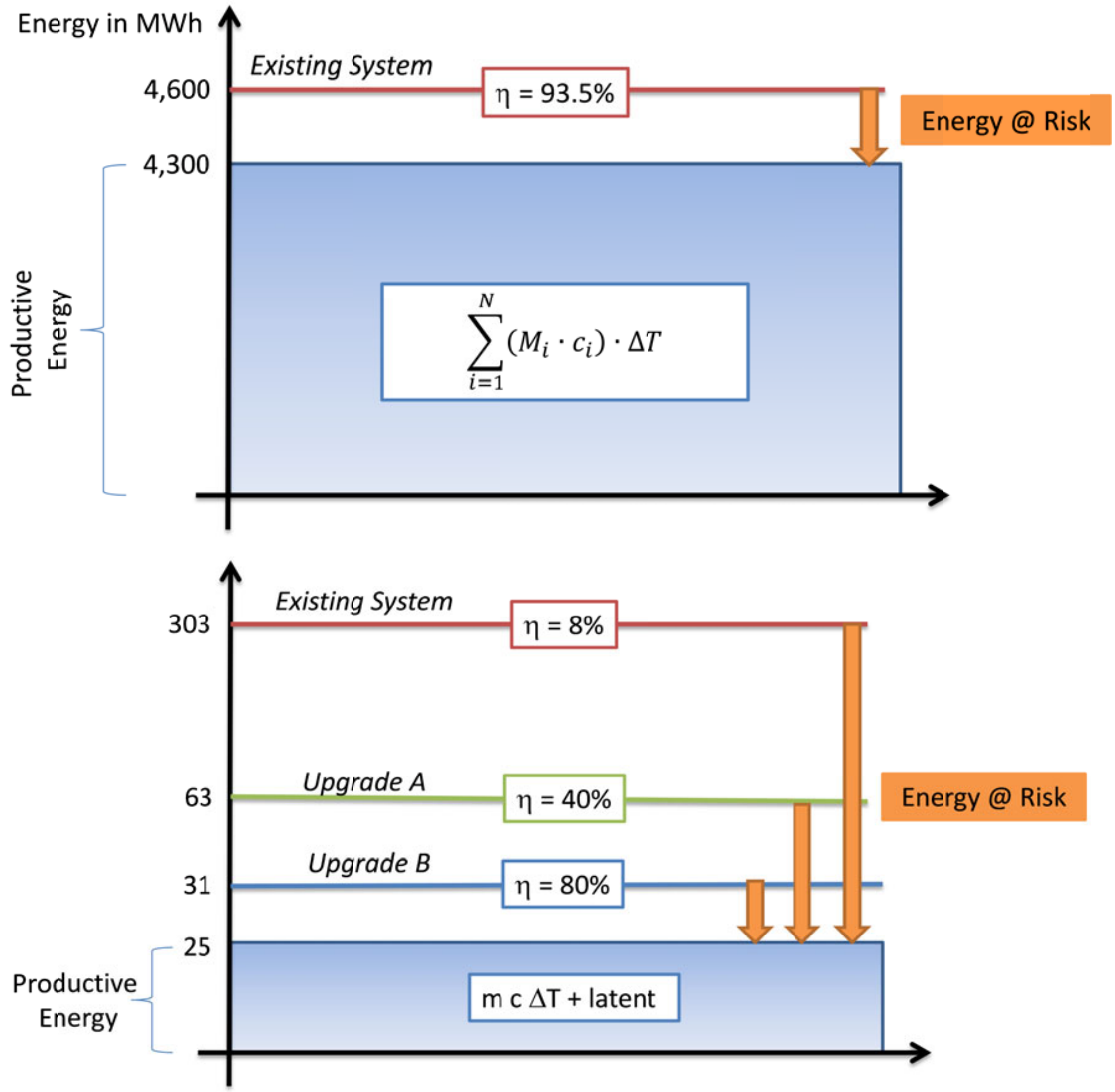
Energy at Risk (E@R) = Energy Used – Ideal Energy

Assessing Conservation Opportunities by Using E@R and BEF Concepts

Figure 3 shows two (real) examples of the energy consumption for two different processes. Prior to any in-depth analysis or study of these two processes, the information available would be the total energy consumption, production and process function in terms of change in material conditions. The energy consumption of 4,600 MWh/annum for Case A would be more than 10 times higher than the energy consumption of Case B (303 MWh).

By applying the E@R and BEF analysis, it would be possible to identify the Energy at Risk not only for the base case (status quo) but also for upgrade options as shown for Case B. It becomes apparent that the energy at risk for Case A is rather small (in relative units) while for Case B it is quite significant. The BEF analysis would have led to a more informed decision on which industrial process to study for energy efficiency opportunities.

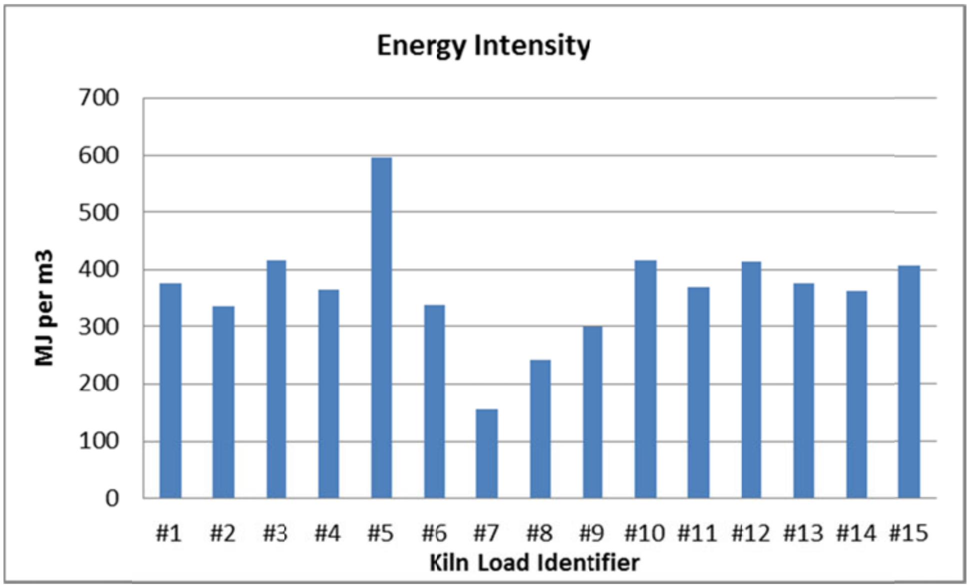
Figure 2. Comparison of Two Industrial Processes: Case A (Top) and Case B (Bottom)



Case Study: BEF of Lumber Drying Kilns

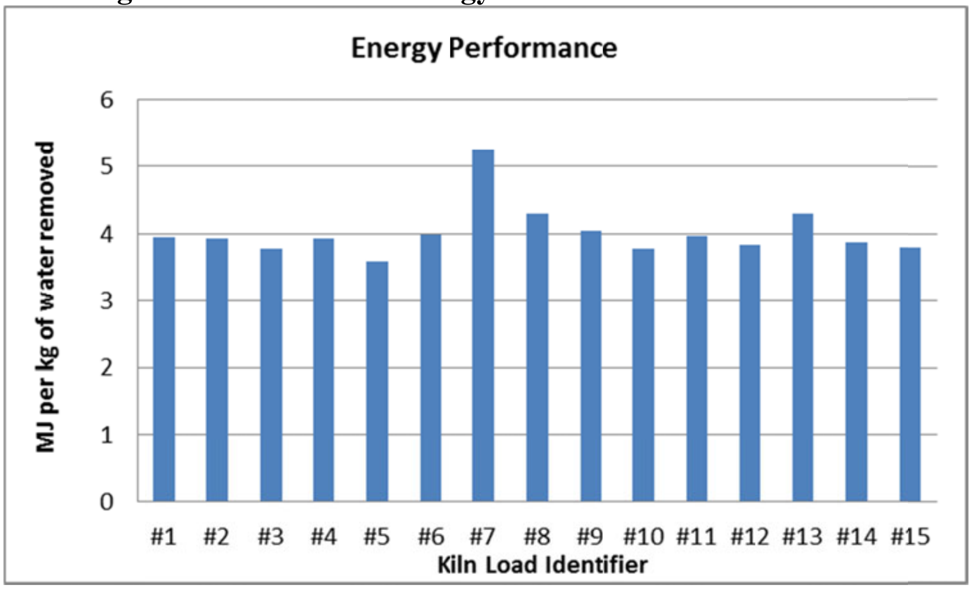
A case study on lumber drying demonstrates the application of the benchmark energy factor comparing the drying efficiency under highly variable material and environmental conditions. After the sawmill cuts timber into dimensional lumber it is kiln dried to improve its structural properties and hence increase its economic value. Kiln drying is the process to remove moisture from the wood and is the highest energy intensive process in a sawmill. The benchmark energy factor provides a universal measure of a lumber drying kiln energy performance compared with what is theoretically achievable in terms of sensible and latent heat transfer and water evaporation rates. The case study includes the evaluation of 15 kiln loads after a kiln energy management control system was installed as the energy efficiency measure. The individual kiln loads are identified as number 1 to 15 in the graphs associated with the case study. As seen in Figure 3, the conventional key performance indicator of energy intensity as a measure of energy per unit of lumber production is highly variable and challenging to develop any accurate energy baseline model. One reason for this high variability in the modeling is that the energy intensity does not include normalization to other more complex energy sensitivities in lumber drying.

Figure 3. Variation in Energy Intensity of 15 Kiln Loads



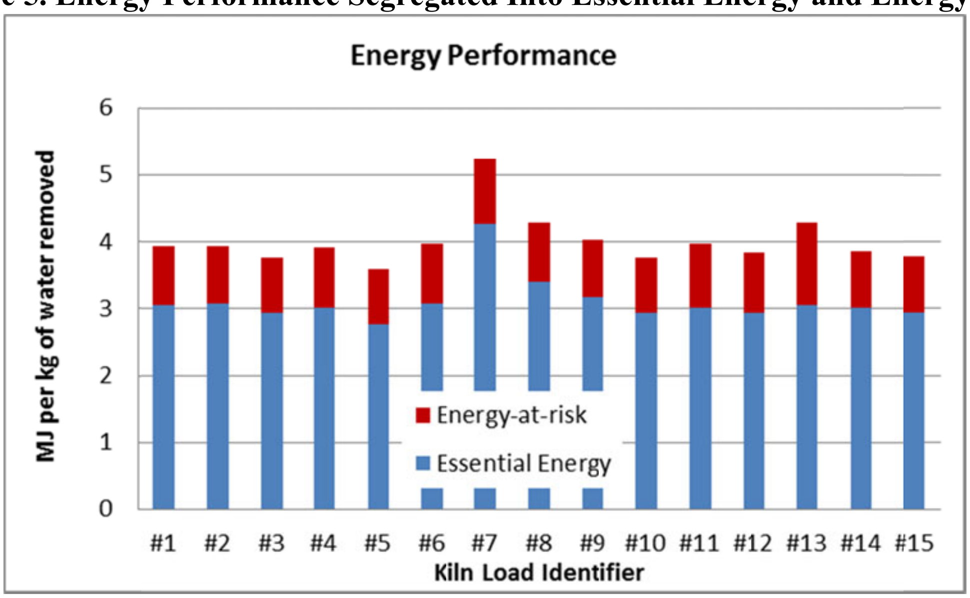
In principle, the process function of lumber drying is to remove moisture from wood so therefore a performance measurement of the energy consumed per kilogram of water removed should be a better indicator of the process energy efficiency. As a result, the variation has improved from four-fold for energy intensity to about two-fold for energy performance as shown in Figure 4. Still, changes in energy performance are difficult to predict or verify because there is no baseline model established and neither is the energy performance separated into components of ideal but non-controllable energy (or essential energy) and the non-productive but controllable energy (or the energy at risk).

Figure 4. Variation in Energy Performance of 15 Kiln Loads



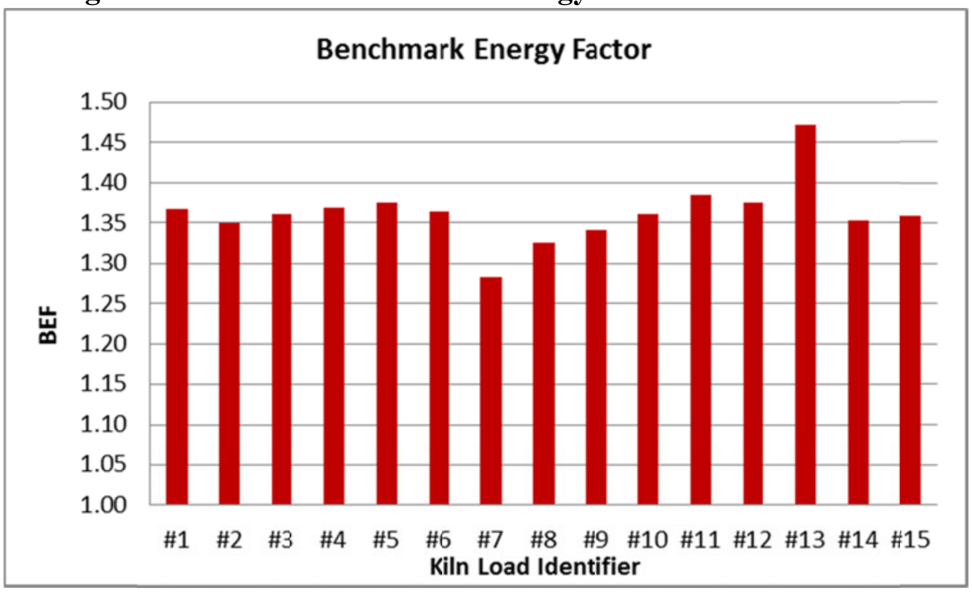
It is not only the production rate and the initial wood moisture content that impacts energy, but also the wood species, wood density, wood thickness and ambient conditions – all of which are all uncontrollable factors. Controllable factors include kiln envelope and insulation, as well as many operational factors such as kiln loading, stacking, drying temperature, drying time, airflow and heat distribution inside the kiln. It would be extremely challenging and require large historic data sets in order to create a reasonably accurate baseline energy model for all scenarios and conditions. The ideal energy model of sensible and latent heat, together with ideal drying rates, is therefore contemplated in order to establish the benchmark energy factor for each kiln load. Based on thermodynamics and established properties from wood sciences, we are able to model the essential energy and its energy at risk as shown in Figure 5.

Figure 5. Energy Performance Segregated Into Essential Energy and Energy-at-Risk



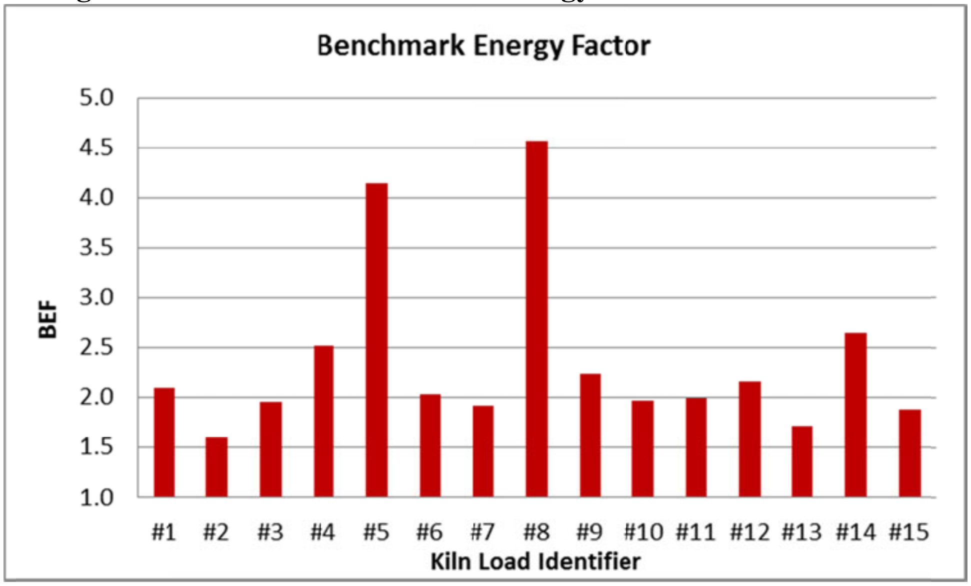
Higher essential energy indicates that the ideal energy is higher because of some uncontrollable factor. The highest sensitivity on the essential energy is the initial moisture content of the wood. Therefore, it is evident that a higher energy performance indicator (kiln load #7) is not always associated with poor overall energy performance (kiln load #13). The theoretical potential for energy improvement is the energy at risk and is best described as the benchmark energy factor as shown in figure 6. Although a BEF of 1.0 can never be achieved, it forms a universal benchmark measure under variable material and environment conditions.

Figure 6. Thermal Benchmark Energy Factor of 15 Kiln Loads



The same approach was also applied to the electrical energy consumption of the kiln circulating fans. The electrical energy benchmark factor had much more variation because at this point in the project, the fan speed was more or less uncontrolled during the drying cycle. The electrical BEF is shown in Figure 7 indicating high BEF for drying cycles exceeding ideal drying hours. The BEF graph together with the input material conditions also shows that the opportunity for electrical energy savings is greater for high initial moisture content wood than for dry lumber. With the benchmark energy factor analyzed for energy efficiency opportunities, it was found that energy-based advanced kiln control and fan speed control with variable speed drives could be adopted.

Figure 7. Electrical Benchmark Energy Factor for 15 Kiln Loads



In summary in the absence of large comparable data sets, a robust and simple energy model has been created that can estimate the 'what would have been' baseline energy performance for lumber drying under almost any material and environment condition. More importantly, we have also created a measure of the absolute technical potential for energy savings, which in this case is between 25% to 45%. Therefore, performance trends over time and individual kiln loads of good and poor performance are easily identified.

Application

Policy Perspective

The benchmark energy factor methodology applied as a rating system for industrial processes could assist government and utilities in meeting energy efficiency objectives. A BEF rating would provide plant management and operators with a targeted indicator, or series of indicators, to enable an assessment of energy performance improvement opportunities and fair comparison of the energy performance of similar processes within a given sector. BEF data could be used by governments to develop a province/state-level energy efficiency potential profile of the industrial sector in order to inform policy development and demand-side management program offerings.

A plant level rating system could be implemented by aggregating BEF's for a plant's most energy intensive process. An aggregate BEF approach would produce a higher resolution plant profile of energy performance similar to the "Process-Step" benchmarking method proposed by Ruth et al. 2001. Like the process step method, an aggregate BEF would effectively draw a boundary around only the most significant areas of process energy in a plant and would thus allow for a streamlined, yet normalized, comparison of plant energy performance within a sector.

Similar to the US DOE's ENERGY STAR Certification program, a BEF rating system could be branded to bring participating plants profile within their sector and supply chain.

Whether applied only at the single process level, or in aggregate at the plant level, BEF ratings could also be used by governments to set energy efficiency targets and negotiate voluntary agreements to meet those targets without prescribing any specific process design or technology.

Technical Perspective

The implementation of BEF can be used to predict and target energy savings more accurately based on the potential for reduction of energy at risk rather than a percentage of total energy consumption. Similarly, the verification and tracking of energy performance can also be made more transparent and consistent if based on the concept of reporting on the differences in the energy at risk.

The BEF is most suitable for industrial processes that have significant energy relationships identified in the benchmark energy model based on physics and engineering principles. For example, any thermodynamic processes that mostly deal with changes in enthalpies like heating water, drying, industrial refrigeration, compressed air systems, pipeline gas compression and even the production of liquefied natural gas. These processes are thus suitable for benchmark energy model development to establish their essential energy requirements. Other applications with variable kinetic energy and potential energy such as pumps, fans and conveying systems would benefit from BEF modeling, thereby identifying areas of energy waste. Also many electro-chemical processes and other chemical processes, including cement and petroleum refining, are intrinsically endothermic or exothermic and have essential energy requirements that should be considered as the fundamental energy allowance when benchmarking, predicting or verifying energy efficiency opportunities. More challenging applications for the proposed energy benchmarking are hard rock milling and mechanical pulping due to many variations in material input and desired material output conditions, but efforts are being made at academic levels to create new benchmark energy models.

The authors believe that this type of energy benchmarking based on ideal energy will better identify the energy gap and drive energy efficiency innovation into industrial processes that can be described in a mathematical energy model. Extremely difficult industries to apply this method plant wide are auto manufacturing, pharmaceutical manufacturing or many small to medium enterprises because their processes are either not very energy intensive or their products vary so much that they cannot be characterized based on a first principles energy approach.

The BEF approach is process specific and full integration to all the processes in an entire plant would be an enormous effort. Therefore, the authors suggest traditional energy mapping be done first to identify areas and processes of relatively high energy intensity. Then, look for high variability in energy intensity and determine whether material or environmental conditions that cannot be influenced have substantial impact on the energy consumption. Fundamentally, the BEF is segregating energy consumption into its components of ideal energy and the energy at risk and therefore, becomes an indicator of the energy efficiency of a process. . This energy intelligence can drive new proactive tools for energy management and empower businesses through risk mitigation to turn energy from a cost into a productive asset.

Summary

Identifying energy saving potentials in industrial systems and processes requires a benchmarking approach that accounts for the complexity and often the highly individualized approach to a given production process. The Benchmark Energy Factor introduced within this paper allows for a normalized comparison of energy performance by taking into account the energy consumption in relation to the input and output materials and their variation over time. The Benchmark Energy Factor methodology enables the identification of the energy at risk, i.e. the controllable energy that does not add value within a given process. Minimizing the energy at risk is the only meaningful approach towards increasing energy efficiency in industrial systems and processes.

Applying the benchmark energy factor methodology as a rating system for industrial processes provides plant management and operators an assessment of energy performance improvement opportunities and has the potential to assist government and utilities in meeting energy efficiency and productivity objectives.

The authors propose to use this method to develop an energy efficiency rating system for industrial processes similar to the U.S. Department of Energy's Energy Star Certification for Plants.

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