THE INSIDE-OUT APPROACH FOR IDENTIFYING INDUSTRIAL ENERGY AND WASTE REDUCTION OPPORTUNITIES

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ABSTRACT
Traditional approaches for reducing energy and waste in industrial processes typically focus on improving the efficiency of the primary energy conversion equipment. Unfortunately, this approach frequently results in incremental improvement at high costs, since most energy and mass conversion equipment is relatively efficient to begin with and upgrading to higher efficiency equipment is usually quite costly. In this paper, we describe an alternative approach that begins by focusing on the eventual end use of the energy and proceeds outward to the distribution system and energy conversion equipment. We call this protocol the inside-out approach, and suggest that it is a manifestation of the exergy analysis method. To support this assertion, we develop the thermodynamic bases for the outside-in and inside-out approaches to identifying savings opportunities. We then demonstrate the comparative effectiveness of the inside-out approach using examples from lighting, air compressors and electro-plating. Finally, we show why the inside-out approach leads to greater sustained savings over time.

INTRODUCTION

In the course of working with industry to reduce their energy use and waste generation, it became apparent that many consultants, vendors of energy-using and waste-treatment equipment, and industrial personnel use a similar method for identifying energy and waste reduction opportunities. When attempting to reduce energy use, attention is initially focused on the flows and costs of energy entering the facility. The search for saving opportunities then moves incrementally inward to the primary energy conversion equipment, such as lights, air compressors, boilers and chillers. In many cases, the "analysis" will end here with the simple solicitation of quotes for higher efficiency equipment. In rare instances, the analysis may move beyond the primary energy conversion equipment to consider the actual manufacturing equipment and processes; however, there is a general reluctance to do this since tinkering with the manufacturing process may negatively affect the sellable product.

Similarly, when seeking to reduce waste disposal costs, the search for savings opportunities usually begins at the plant boundary with the solicitation of less-costly waste disposal services. The search for savings opportunities then moves incrementally inward to consider on-site waste treatment. As before, there is a general reluctance to move further inward to the actual manufacturing processes, where much of the waste is generated, because of the risk of adversely affecting the sellable product.

We call this the outside-in approach, since the analysis begins at the plant boundary and works incrementally inward toward the actual manufacturing processes. Over time, the limitations of the outside-in approach have become more and more apparent to us. In our experience, this approach for reducing energy use and waste generation typically results in incremental improvement at high costs. Despite these meager results, many companies believe that they have accomplished all that is possible.

In response to these limitations, we have developed a protocol for identifying savings opportunities that is essentially the opposite of the outside-in approach. We call this protocol the "inside-out" approach since the analysis begins at the heart of the plant, with the equipment that actually manufactures the product, and works outward (Figure 1). When seeking to reduce energy costs, we sequentially analyze the manufacturing equipment and processes, the energy distribution systems, the primary energy conversion equipment, and finally the utility services. In the case of waste reduction, we also begin and the primary manufacturing equipment and processes, work outward to any waste treatment equipment and finally analyze the waste disposal services. By first looking for savings opportunities at the heart of the manufacturing process, and then working out toward the plant boundary, savings are multiplied because distribution systems, energy conversion equipment and waste treatment processes can be downsized or eliminated.

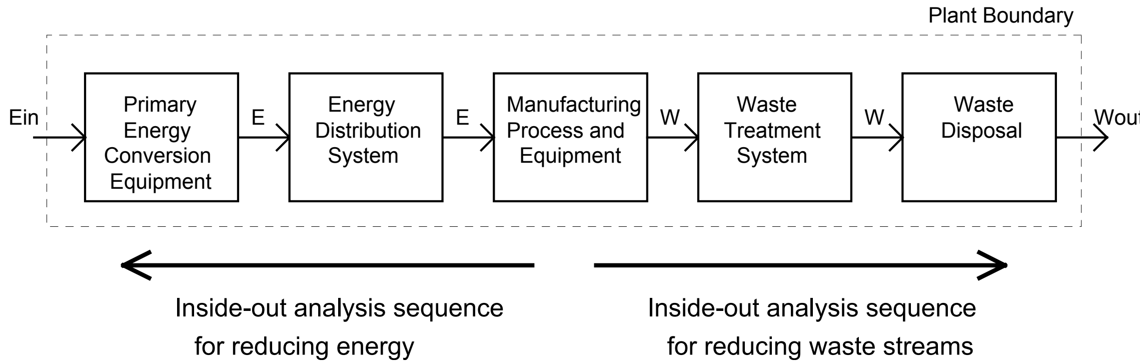

Figure 1. Schematic representation of the inside-out approach for identifying energy and waste reduction opportunities. E represents the flow of energy and W represents material waste streams.

At the same time that we were realizing the limitations of the outside-in approach, we also became cognizant of the limitations of traditional energy-based analyses. Unfortunately, simple application of the principles of conservation of energy and mass to energetic systems frequently results in a poor understanding of the actual resource efficiency. A better description of the resource efficiency results from applying a combination of the First and Second Laws of Thermodynamics using property called exergy. Exergy analysis acknowledges that something is destroyed in all real processes, and directs our attention to the internal workings of the process.

In this paper, we posit that the outside-in approach is conceptually derived from the principles of conservation of energy and mass, whereas the inside-out approach is derived from the principles of exergy analysis. We develop the thermodynamic bases for these two approaches, and demonstrate the comparative effectiveness of the inside-out approach for identifying savings opportunities using examples from lighting, air compressors and electro-plating operations. Finally, we show why the exergy-based, inside-out approach leads to greater sustained savings over time.

ENERGY ANALYSIS AND THE OUTSIDE-IN APPROACH

The principle of conservation of energy, as embodied in the First Law of Thermodynamics, is conceptually well understood by people both with and without scientific training. According to the First Law, energy can be converted to different forms but is never created or destroyed. Thus, energy is conserved in all processes, and a simple accounting of the input and output of energy flows describes a system's energy efficiency.

Consider, for example, the generic energy conversion device shown schematically in Figure 2. Primary energy, E_{in}, is added to the device. Some of this energy is lost during the conversion process and as is dissipated as waste heat, E_{waste}. The remainder of the primary energy is effectively converted to the desired form and delivered to the intended process as E_{useful}. This generic system would describe a boiler or furnace, where natural gas energy is added, some heat is lost up the exhaust stack, and the remaining heat energy is delivered to the end use. It would also describe a motor, an engine, and several other common energy conversion devices.

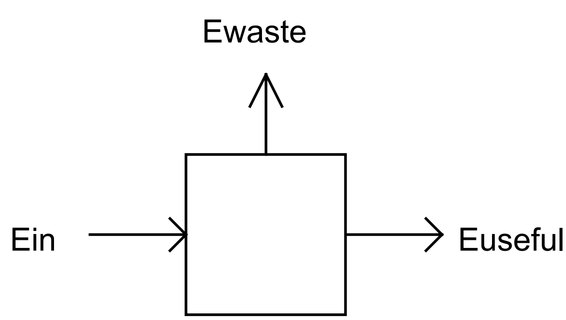

Figure 2. Energy flows entering and exiting a typical energy conversion device such as a furnace, boiler, motor or engine.

When we use this model to understand energetic systems, it quickly becomes apparent that we don't need to know anything about the internal workings of the device, since its efficiency is completely described by a boundary analysis. Energy accounting tells us that in steady state operation the useful energy out is the difference between the energy input and the energy losses. Thus, improving the resource efficiency of this system depends solely on minimizing the energy in the waste stream E_{waste}.

$$E_{useful} = E_{in} - E_{waste} \tag{1}$$

The similarities between energy analysis and the outside-in approach are striking. Both the outside-in approach and energy analysis focus attention on the flows crossing the system boundary and implicitly ignore the internal workings of the system. Because of these similarities, we suggest that energy analysis is the thermodynamic basis of the outside-in approach to resource efficiency.

EXERGY ANALYSIS AND THE INSIDE-OUT APPROACH

The inside-out approach has its thermodynamic roots in exergy analysis, which is a combination of the First and Second Laws of Thermodynamics. The Second Law states that the disorder or randomness of any closed system, as measured by its entropy, increases during all energetic processes. The Second Law acts as a one-way sign, signaling the impossibility of energetic processes to run in reverse (because of this, the Second Law has been called the "arrow of time"). When the first and second laws are combined, a new property called exergy can be formulated (see for example Moran, 1982; Cengal and Boles, 1994; Bejan et al., 1996; etc.). Exergy is the maximum useful work that a system can produce as it comes into equilibrium with the environment.

In contrast to energy, which is always conserved, some exergy is destroyed in all real processes. Thus, exergy analysis is consistent with our intuition that something is irretrievably lost when a tank of gas is consumed while driving a car or a log is burned to heat a house. An exergy analysis of the same system shown in Figure 2, would not only account for the exergy flows crossing the system boundaries, X_{in}, X_{waste} and X_{useful}, it would also account for the exergy destroyed *within* the process, $X_{destroyed}$ (Equation 2).

$$X_{useful} = X_{in} - X_{waste} - X_{destroyed} \tag{2}$$

The quantity of exergy associated with each flow depends explicitly on the type, pressure, temperature and composition of the flow. Thus, highly ordered forms of energy, such as work, chemical energy, and heat at high temperature, have greater exergy than disordered forms of energy such as heat at low temperature. Because of this, the quantity of exergy destroyed is a function of the difference between the exergy in and the useful exergy delivered to the process, X_{in} - X_{useful}, (Equation 3).

$$X_{destroyed} = (X_{in} - X_{useful}) - X_{waste} \tag{3}$$

Thus, minimizing $X_{destroyed}$ depends on matching the exergies of the incoming and outgoing flows. For example, if a process requires low-quality energy, such as low-temperature heat, then minimizing $X_{destroyed}$ requires that the process be supplied with a low-quality source of energy; if a high-quality energy source is used, exergy will be unnecessarily destroyed, resulting in a waste of energy resources.

In conclusion, exergy analysis is able to identify losses that occur within the system boundary, whereas energy analysis can only identify losses that cross the system boundary. Thus, exergy analysis, like the inside-out approach, focuses our attention on the internal workings of a piece of equipment or plant. Similarly, exergy analysis is able to identify the losses that occur due to a mismatch between the energy resource and the end-use, whereas energy analysis cannot. Hence, maximizing the resource efficiency of industrial processes begins with a knowledge of the end use of the energy in the manufacturing process. These considerations suggest that the inside-out approach, which also focuses attention on the manufacturing process, is simply a manifestation of the exergy analysis method.

COMPARISONS OF ENERGY AND EXERGY ANALYSES OF INDUSTRIAL SYSTEMS

Despite the widespread use of energy analysis to describe industrial systems, energy analysis alone can frequently give an incomplete and misleading picture of the resource efficiency of a process and the opportunities for resource minimization.

Consider, for example, a throttling process in which steam pressure is reduced adiabatically from 500 psia and 700 F to 15 psia and 644 F. An energy analysis of this system would conclude that the enthalpies of the entering and exiting streams are equal, and hence no energy is lost and the process is 100% efficient. Although this is thermodynamically correct, something is intuitively wrong with this conclusion. Clearly, steam at 500 psia and 700 F has a greater potential to do work or transfer heat than steam at atmospheric pressure and 644 F. Exergy analysis, in contrast, captures this loss. In an exergy analysis, the specific exergies of the entering and exiting streams are 524 Btu/lbm and 326 Btu/lbm respectively; thus, 38% of the potential to do useful work is lost during this process. Exergy analysis correctly shows how throttling processes, and all pressure drops, are wasteful and should be avoided, while an energy analysis of the same process would identify no potential for resource reduction.

Next, consider the common practice of using a natural gas furnace to provide space heat to a facility when the ambient temperature is about 32 F. Condensing natural gas furnaces are now available with energetic efficiencies of 97% and higher. At first glance, this might suggest that space heating is nearly as efficient as possible, and that no substantial improvement is possible. An exergy analysis, however, takes into account the huge mismatch between the 3,000 F temperature of the combustion gasses and the 81 F temperature of the facility. Because of this mismatch, the exergetic efficiency of the furnace is only about 7%; thus, 93% of the potential of the natural gas to do useful work is wasted! In comparison, a 60% efficient solar heating system operating at 176 F would have an exergetic efficiency of 24%, over three times greater than the natural gas furnace. This example emphasizes the importance of matching the energy resource to the end-use, a concept that is invisible to energy analyses.

Finally, consider the common practice of industrial air compression. When the system is defined as the air compressor, the after-cooler and storage tank, the temperatures of the air entering and leaving the compressor system are nearly identical. Under these conditions, the enthalpies of the air before and after compression are equal, and the process has an energy efficiency of zero since no useful energy is added to the compressed air stream. In contrast, the exergetic efficiencies of typical industrial air compressor operations range from about 17% to 56%, with the higher efficiencies resulting from fixing leaks, compressing cooler outdoor air, lowering the set-point pressure, reclaiming waste heat and properly sizing the air compressor (Bader, 2000). Once again, the exergetic analysis proved useful in quantifying resource minimization opportunities, where an energy analysis did not.

As these examples demonstrate, energy analyses are often unable to characterize the true losses and efficiencies of industrial processes. In contrast, exergy analyses typically provide a much more accurate description of the thermodynamic performance of the system, and hence are better able to identify the best opportunities for resource minimization. This suggests that use of the inside-out approach for identifying resource efficiency opportunities, which is based on an exergy analysis method, would also improve the identification of resource saving opportunities.

THE INSIDE-OUT APPROACH FOR ANALYZING LIGHTING SYSTEMS

We have reviewed several proposals for lighting upgrades by lighting contractors to industrial clients. In most cases, the proposals consist of simply replacing the current lights with higher-efficiency lights. This is a classic example of the outside-in approach, since it focuses on the primary energy conversion equipment without considering the end-use or distribution system. In contrast, the inside-out approach begins by evaluating the end-use, then the distribution system, and, finally, the primary energy conversion equipment, the lights. In our experience, this approach routinely results in significantly greater savings at lower first costs than could be achieved by simply installing higher-efficiency lights. The inside-out protocol, as applied to lighting systems, is discussed in the sub-sections that follow.

Evaluate the End-Use

With lighting systems, the first step in evaluating the end use is to assess the quantity and quality of lighting in the plant. To assess the quantity of light, compare measured and recommended lighting levels throughout the plant. In some cases, lighting levels may by unnecessarily high, resulting in immediate savings opportunities. In other cases, lights may be left on even when there is no activity within a space. Turning off unnecessary lights can also result in significant savings opportunities.

Lighting quality issues include glare, color rendition and psychological effects. Several studies have demonstrated that well-lighted work places have higher productivity, lower absenteeism and higher morale. In most cases, the revenue generated by even a small increase in productivity will vastly exceed the cost of a lighting retrofit (Romm and Browning, 1996). Use of these techniques, frequently results in significant savings, before the lighting distribution system or lighting equipment are even considered.

Evaluate the Distribution System

For lighting systems, the distribution system includes reflectors, lenses, the positioning of lights, and any other factor that influences the distribution of light within the work place. A close inspection of the lighting distribution system will frequently reveal opportunities to reposition lights blocked by scaffolding or over underused areas. In addition, dark walls and ceilings tend to absorb rather than reflect light. In other cases, the lights can be lowered, or task lighting installed, to direct light to where it is most needed. Lighting fixtures and lenses absorb and block some the light generated by the lamps. The efficiency of transmission can be improved by cleaning reflectors and fixtures, and cleaning or removing unneeded, dirty or yellowed lenses.

Reducing distribution losses typically reduces the number of lights needed to supply the required light to the work area.

Evaluate the Primary Energy Conversion Equipment
As a last step, consider the primary energy conversion equipment, the lights. In some cases, daylighting can replace most of the electric lighting. Sunlight is abundant, free and the best type of light for virtually all visual tasks. Our eyes evolved to see objects illuminated by sunlight. Thus, we have better visual accuracy and color rendition in sunlight than under electrical lights. Sunlight also has packs more visible light into each watt of energy; thus, cooling loads are reduced in daylit buildings. Finally, several studies have concluded that employee moral and productivity increases in daylit buildings (see for example: Romm and Browning, 1996; Heschong, 1999). Not surprisingly, the use of daylighting instead of electric lighting results in significantly less destruction of exergy to per perform the required lighting task, because of the close match between the exergy supplied and required.

In other cases, it may be appropriate to replace the current lights with higher-efficiency lights. However, if lighting quantity and quality issues have been properly addressed and distribution losses minimized, the expense of converting to and operating higher-efficiency lights will be dramatically reduced. In our experience, the use of this inside-out protocol for reducing lighting energy use results in significantly greater savings than are achieved by simply replacing the lighting equipment.

THE INSIDE-OUT APPROACH FOR ANALYZING COMPRESSED AIR SYSTEMS

When a pneumatic machine begins to malfunction because it is under pressurized, the knee-jerk response is typically to purchase a bigger air compressor. This is a classic outside-in approach because it focuses on the energy conversion equipment rather than the end-use of this equipment in the manufacturing process. Unfortunately, most air compressors have poor part-load efficiencies and a bigger air compressor ends up significantly increasing operating, replacement and first costs.

The inside-out approach is to first examine the end-uses for leaks and inappropriate uses of compressed air. Can the process be rescheduled when more compressed air is available? Next examine the distribution system for excessive pressure drop and to ensure adequate compressed air capacity in storage tanks. Frequently, minimizing the end-uses for compressed air and improving the distribution system can solve the problem without purchasing a new compressor. As a last step, check the air compressor itself for savings opportunities. This approach regularly reduces operating costs without significant first costs and stands in stark comparison to the air-compressor first approach.

THE INSIDE-OUT APPROACH FOR ANALYZING ELECTRO-PLATING WASTEWATER

In many cases, the negative economic consequences of the wrong analysis sequence are irreversible. After expensive, oversized equipment has been purchased, there is nothing that can be done.

For example, in response to potential EPA regulations, one company built a multi-million dollar waste treatment facility to clean wastewater from a plating operation. Unfortunately, this decision was fully implemented before we arrived to do an assessment. Despite this fact, we began analyzing the wastewater stream generated by the plating operation using the inside-out method. Our first step was to question the need for the process. This initiated a spirited debate among management as to whether it was cheaper to outsource the entire plating process. Thus, the entire waste stream may have been eliminated through a corporate policy decision. Next, by looking at the plating line, we found that through a few simple measures, such as delaying the dip rate and employing counter-current rinse tanks, the quantity of waste water could be reduced from 100,000 gallons per day to about 10,000 gallons per day. If this had been done initially, the initial cost and operating costs of the wastewater treatment plant could have been dramatically reduced. In addition, the increased concentration of chemicals in the low-flow design would have enabled the company to recycle plating chemicals from the effluent. This would have saved the company hundreds of thousands of dollars per year in reduced chemical costs. In this example, failure to analyze the waste stream using the inside-out approach has cost the company millions of dollars in initial and operating costs.

SUSTAINING RESOURCE EFFICIENCY EFFORTS

A central reason for the success of the inside-out approach is that it capitalizes on what manufacturing companies know best: their products and processes. The inside-out approach internalizes the resource minimization process by asking designers, schedulers, managers, equipment operators and maintenance staff to use their expertise in the product and process to reduce resource use and costs. The result is that this approach is more likely to foster internal, ongoing resource minimization efforts. This stands in sharp contrast to the traditional outside-in approach, in which attention is focused on support equipment and waste streams that are not the company's primary business. Because of this, there is often little in-house expertise about process support systems, and resource minimization becomes a periodic and extraneous task that often relies on outside experts.

SUMMARY AND CONCLUSIONS

To maximize resource efficiency, it is necessary to employ the proper analytical method and sequence. Exergy analysis is shown to be a better indicator of process efficiency and potential savings than simple energy-based analysis because exergy analysis is able to quantify losses that are internal to the system and losses that result from a mismatch between energy supply and end use. The exergy analysis method also suggests a proper sequence of analysis, which begins by analyzing the primary manufacturing processes and proceeds outward to the distribution and waste treatment systems and finally to the primary energy conversion or waste disposal equipment. We call this analysis protocol, the inside-out method.

In most cases, use of exergy analysis method and the inside-out protocol multiplies savings, since minimizing end-use loads in the manufacturing processes reduces the expense of and losses from the distribution system, which in turn reduces the expense of modifying and losses from the primary energy and material conversion equipment. The examples presented in this paper illustrate the benefits of using these methods. In addition, use of the inside-out method promotes a corporate culture that sustains the resource-efficiency efforts over time. In our experience, the big savings are in the process, and not in the incremental improvement of energy conversion or end-of-tailpipe technologies.

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