Integrated Systems Plus Principles Approach to Industrial Energy Efficiency

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ABSTRACT

In today's global economy, fierce competition, volatile energy costs and a shared motivation to reduce the environmental impacts of energy use drive improvements in manufacturing energy efficiency. This paper presents a systematic approach for improving industrial energy efficiency that breaks complicated manufacturing processes down into distinct energy systems that can be addressed using seven fundamental principles of energy efficiency. This "Integrated Systems plus Principles Approach" (ISPA), based on the experience of 850 industrial energy audits, focuses on the electrical distribution, motor drive, lighting, fluid flow, compressed air, process heating, process cooling and space conditioning systems that make up virtually all manufacturing processes. Targeting these systems, rather than individual manufacturing processes, makes it possible to develop expertise in a finite group of energy systems rather than a nearly infinite number of manufacturing processes. In addition, seven principles of energy efficiency have been identified that apply across all systems and provide a unified way of understanding and approaching energy saving opportunities. The seven principles of energy efficiency are "think inside out", "maximize control efficiency", "employ counter-flow", "avoid mixing", "match source energy to end use", "benchmark against theoretical minimum energy use", and "consider whole systems over whole time frames". This paper explains ISPA, discusses the use of ISPA for conducting energy assessments and teaching energy efficiency. Finally, it presents a public-domain, open source, spreadsheet-based "Energy Efficiency Guidebook" based on ISPA that combines the principles of energy efficiency, system best practices and energy saving examples with spreadsheet calculators and energy simulation software to quantify savings.

Introduction

The U.S. Department of Energy funds 24 Industrial Assessment Centers at major universities to perform 20 energy audits per year on mid-sized industrial facilities. The program, which began in 1978, has been highly successful; by the year 2012, on average each assessment leads to potential cost-effective energy reductions of about 8% (IACD 2012). In addition, this program provides direct experience in industrial energy efficiency for about 250 engineering students each year (AMO 2013).

However, the US Census Bureau reports that there are 330,611 manufacturing facilities in the U.S. (USCB 2007). Thus, it would take 24 existing centers performing 20 audits per year almost 700 years to audit them all. Even though many energy consulting companies offer energy auditing services as well, they are still limited in the number of clients that they can serve. On the industry side, manufacturers looking to cut costs and reduce their carbon footprint often lack in-plant expertise in energy efficiency. Without a systematic approach to industrial energy efficiency, plant personnel assigned to the task often do not know where to begin the search for savings, and as a consequence the process is frequently focused on a few pieces of energy conversion equipment such as air compressors, boilers, and chillers and relies heavily on equipment vendors for advice. This “outside in” approach typically leads to small energy savings with large first costs. Even when a few energy saving opportunities are identified using this hit or miss approach, the lack of a systematic procedure misses many saving opportunities. Because of this, some organizations have developed their own approaches to energy efficiency. For example, the American Society of Mechanical Engineers provides system assessments standards and guidance for the Superior Energy Performance certification program for Process Heating, Pumping, Steam and Compressed Air systems (ASME 2010). Similarly, the ASHRAE Commercial Building Energy Audits also have a step of breaking down a building’s end use in a systematic approach (ASHRAE 2011).

In our view, the energy auditing approach for manufacturing can be dramatically improved by understanding plant energy use in terms of primary energy systems and principles of energy efficiency. Over the last three decades the University of Dayton Industrial Assessment Center (UD-IAC) has performed over 850 industrial energy assessments, graduated over 70 IAC students, and taught industrial energy efficiency to hundreds of other students and manufacturers around the world. These experiences have led to the development of a coherent, reproducible, and teachable approach to manufacturing energy efficiency: the Integrated Systems plus Principles Approach (ISPA). ISPA focuses on energy systems rather than specific production processes or equipment, and applies seven principles of energy efficiency to all systems. To support ISPA, a comprehensive toolkit has been developed which puts the power to identify and calculate savings in the hands of the user. The Energy Efficiency Guidebook (EEG) combines the principles of energy efficiency, system best practices and energy saving examples with spreadsheet calculators and energy simulation software to quantify savings. The following sections introduce the approach to identifying energy systems, the principles of energy efficiency, and the EEG.

Industrial Energy Systems

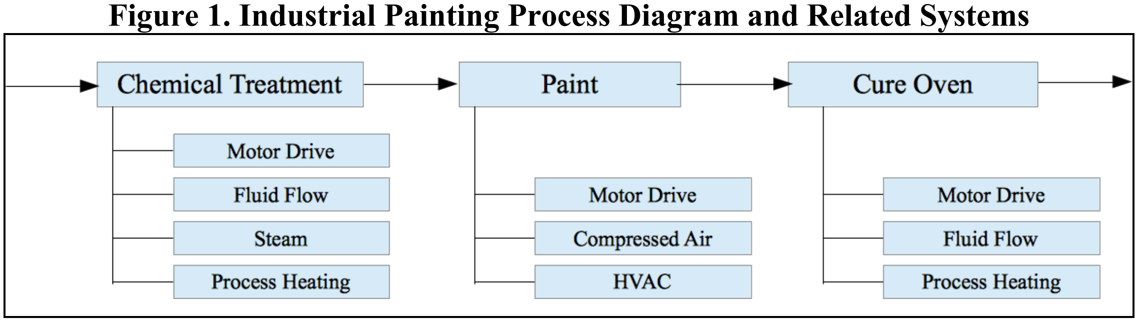
Virtually all manufacturing processes are comprised of some combination of twelve distinct energy systems: Electrical Distribution, Lighting, Motor Drive, Fluid Flow, Compressed Air, Steam, Process Heating, Process Cooling, Industrial Refrigeration, HVAC, Combined Heat and Power and Renewable Energy Systems. Each of the systems is comprised of primary energy conversion equipment, energy distribution equipment and some end-use of the energy. For example, in lighting the primary energy conversion equipment is the lamp, the distribution equipment is the reflector or fixture and the end use is the quantity and quality of light delivered to occupants. Similarly, in compressed air, the primary energy conversion equipment is the air compressor, the distribution equipment is the pipes and hoses and the end use is the pressure and quantity of compressed air delivered to the user. Table 1 lists common pieces of equipment associated with each energy system.

Table 1. Energy Systems and Some Related Equipment

System	Related Equipment
Electrical Distribution	Transformers and capacitors
Lighting	Lighting fixtures, occupancy sensors, windows and skylights
Motor Drive	Motors, belt drives, controllers
Fluid Flow	Pumps, fans, pipes, ducts, fittings
Compressed Air	Compressors, dryers, storage, piping, end use tools
Steam	Boilers, piping, fittings, steam traps, heat exchangers, de-aerators
Process Heating	Ovens, furnaces, heat exchangers
Process Cooling	Chillers, cooling towers, heat exchangers
Industrial Refrigeration	Ammonia compressors, evaporative condensers, evaporators, controls
HVAC	Chillers, air conditioners, package units, make-up air units, heaters, fans
Combined Heat and Power	Engines, turbines, fuel cells
Renewable Energy	Photovoltaic systems, solar thermal systems, wind turbines

Breaking a manufacturing process down into these distinct energy systems allows the analyst to approach almost any process with confidence. Consider, for example, the case of a painting process diagramed in the Figure 1. Parts in this process undergo chemical treatment before being painted and cured. At first glance, locating energy savings opportunities in this process may seem daunting, especially if one has never seen a painting operation before. However, if energy systems can be identified, the path becomes clearer. The solutions and rinse water in chemical treatment dip tanks are often circulated and heated with steam, so this process involves fluid flow and steam systems. In the painting stage, compressed air powers paint sprayers and agitators, so this process involves compressed air. Paint booths maintain temperature and humidity, so this process involves HVAC systems. The moving heated air in the curing oven involves process heating and fluid flow systems. Fluid pumps, material conveyors, and ventilation fans are all powered by electric motors, and thus motor systems are present in every stage. Thus, applying best practices from these energy systems allows an analyst to effectively identify energy saving opportunities even when unfamiliar with a specific manufacturing process.

Figure 1. Industrial Painting Process Diagram and Related Systems



In addition, an energy "system" approach allows the interactions between system components to be considered. Thus, the important interactions between end-use, distribution and energy conversion components of a system can be considered simultaneously. For this reason, U.S. Department of Energy tools, such as AIRMaster+, PSAT and PHAST (AMOTD) employ this system approach. For example, in a compressed air system, reducing compressed air pressure reduces both compressor power and compressed air leakage. Similarly, establishing night and weekend setbacks for space heating reduces both energy consumption of the heaters and the heat loss through building envelope. In some cases, interaction affects between energy systems may afford additional energy saving opportunities and these cases should be considered. For example, improving lighting efficiency also reduces space cooling requirements. However, breaking processes into energy systems and considering all components within a system typically covers the majority of important interaction effects.

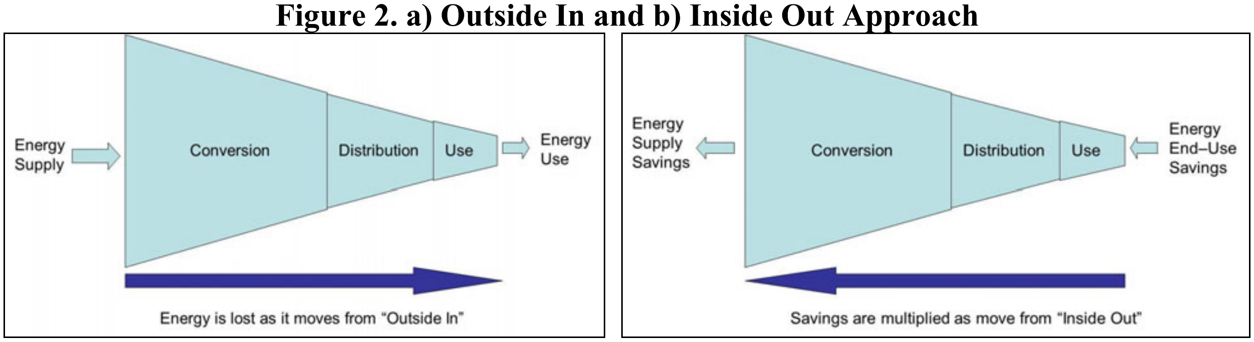
Principles of Manufacturing Energy Efficiency

As useful as an energy systems approach is, it can be enhanced by an understanding of energy efficiency principles that apply across multiple energy systems. The list of seven energy efficiency principles considered here is not comprehensive; however, in our experience these seven apply to multiple, if not all, energy systems and have proven to be excellent guides to energy efficiency. Some of these principles, such as "Think Inside Out", "Maximize Control Efficiency" and "Consider Whole Systems Over Whole Time Frames" are a function of the systemic nature of energy use systems and the way these systems must be designed, controlled and paid for. Other principles, such as "Employ Counter Flow" and "Avoid Mixing" are derived from exergy analysis, which is able to quantify losses from heat transfer through a finite temperature difference, mixing and friction. Together, this tool kit of energy efficiency principles provides continuity to the approach for identifying energy saving opportunities within and across energy systems. The following sections describe these principles and provide an example or two of the application of each principle to an energy system.

Think Inside Out

In each energy system, energy which enters the plant from the "outside", is converted into a useful form, distributed, and finally used on the "inside" as shown in the left of Figure 2a. Each step has an associated efficiency, with inherent energy and/or exergy losses. Thus, delivered energy is reduced as it flows from outside to inside.

Figure 2. a) Outside In and b) Inside Out Approach



The inside-out approach to identifying savings opportunities, as shown in the right of Figure 2b, begins on the inside of the plant with the end-use and asks how much and what type of energy is required to accomplish the objective. Only after the appropriate type of energy has been determined and end-use energy minimized, is the distribution system analyzed for efficiency opportunities. Only then, after all distribution efficiency opportunities have been identified, is the energy conversion equipment considered. Using this approach, energy savings identified on the "inside" are multiplied as they pass back to the "outside". Table 2 demonstrates the power of inside-out thinking. Saving 1 kWh of energy by reducing pipe friction on the "inside" results in 5.55 kWh of fuel savings at the power plant.

Table 2. Energy Systems and Related Equipment

Inside-out Thinking Elements	Efficiency	Savings (kWh)
Reduce pipe friction	-	1.00
Pump	70%	1.43
Drive	95%	1.50
Motor	90%	1.67
Transmission and distribution	91%	1.83
Power plant	33%	5.55

Since it focuses on the end use first, rather than large pieces of conversion equipment, the inside-out approach consistently identifies more savings at a lower first cost than "outside-in" approaches. Finding significant savings opportunities at the end use and in the distribution system regularly results in the downsizing of conversion equipment and the reduction in the control losses associated with oversized equipment. In addition, systematic application of the inside-out approach ensures that all energy interactions within a system have been considered; thus, it is essential to a comprehensive understanding of energy saving potential.

Maximize Control Efficiency

Most engineering systems are designed for peak load, a condition that inherently only occurs once. However in practice, most systems operate at part load most of the time, so that the output of most energy conversion equipment must be controlled to meet the load. Further, the energy efficiency of most energy conversion equipment varies with the load. Thus, recognizing and modifying systems with poor part-load efficiency can result in significant energy savings.

Consider Figure 3 with energy use on the vertical axis and production output (load) on the horizontal axis. Most systems use peak energy at peak production, but unfortunately, many energy systems, such as constant-speed pumping with by-pass and blow-off air compressor control, continue to use peak energy even as production (load) declines. This is represented as the top line. The best control efficiency is represented by the bottom curve, which is typical of the use of variable speed drives in fluid flow systems. Because of the magnitude of losses associated with poor part-load control, it is important to determine the control efficiency of every system and whether it can be improved.

The importance of maximizing control efficiency can be illustrated by considering compressed air systems. Figure 4 is a graph representing the different control strategies for air compressors. The Y-axis is fraction power, or the fraction of the compressor's full load power, and the X-axis is fraction capacity, or the fraction of the compressor's full air output. The most common forms of compressor control are modulation, load/unload, and variable speed. As seen in the graph, when the compressor is producing no air, modulation and load/unload controls may only reduce the fraction power to about 70% or 50% respectively. High efficiency flow control methods like variable speed drives follow load closely, and can push the fraction power at no production down to as low as 10%.

Figure 3. Control Efficiencies

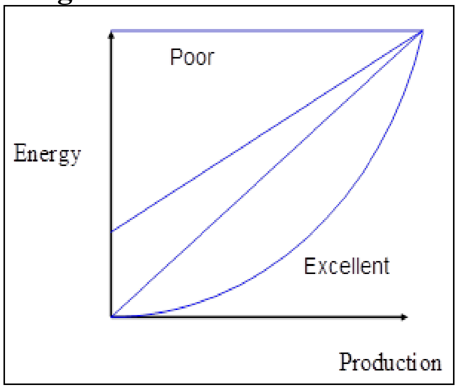
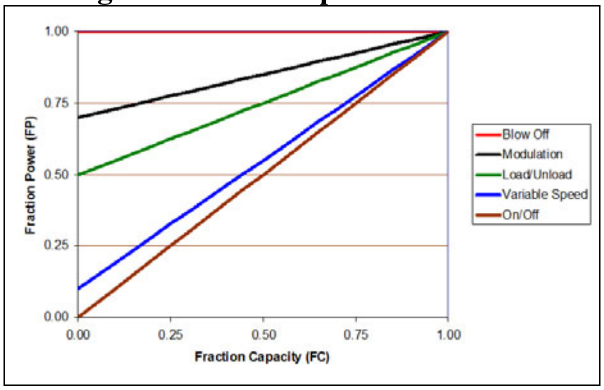


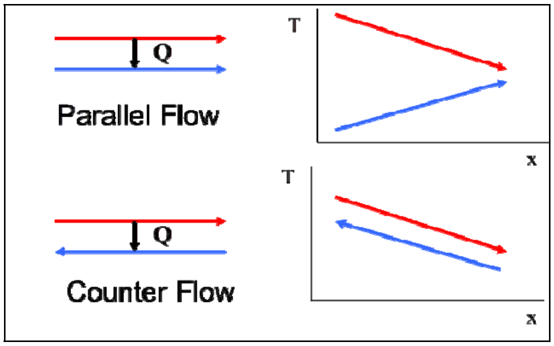
Figure 4. Air Compressor Control



Employ Counter-Flow

Figure 5 depicts parallel-flow and counter-flow heat exchange. In parallel-flow heat exchange, both the hot and cold fluids travel in the same direction. As heat is exchanged from the hot to the cold fluid, the temperature of the hot fluid declines and the temperature of the cold fluid increases. However, the outlet temperature of the hot fluid can never drop below the outlet temperature of the cold fluid. In counter flow heat exchange, the hot and cold fluids travel in opposite directions. As heat is exchanged, the temperature of the hot fluid declines and the temperature of the cold fluid increases. However, the outlet temperature of the hot fluid can approach the inlet temperature of the cold fluid, which results in greater heat transfer. Thus, counter-flow heat exchange is inherently more effective than parallel-flow or cross-flow heat exchange. This improved heat exchange effectiveness reduces losses and results in energy savings.

Figure 5. Parallel Flow and Counter Flow Heat Transfer



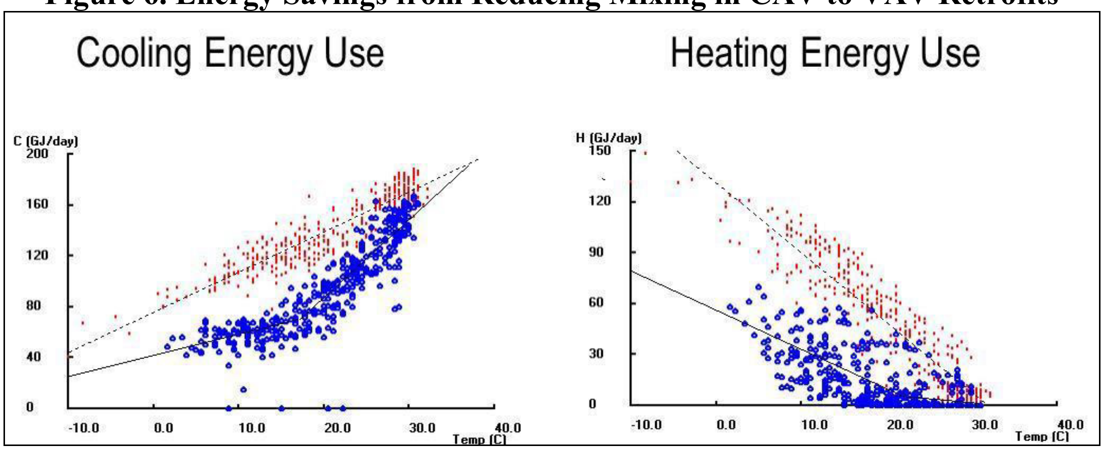
Consider for example, heat exchange between hot combustion gasses and a product. In parallel flow, the exhaust gasses can never be cooler that the final temperature of the product. In high-temperature melting and heat treat operations, this forces the temperature of the exhaust combustion gasses to remain quite high, with corresponding high energy losses. If the configuration were converted to counter flow, the temperature of the exhaust could approach the entering temperature of the product, which is typically room temperature. Thus, low temperature exhaust gasses carry away much less energy and the heating process is more efficient. This is just one example of how counter flow heat exchange improves energy efficiency.

Avoid Mixing

Exergy analysis shows that useful work is always destroyed with mixing. In manufacturing, mixing streams with different temperatures, pressures or humidity frequently results in additional energy use. Thus, minimizing mixing usually saves energy.

For example, consider air distribution systems to provide heating and cooling for buildings. Constant-air-volume (CAV) systems mix hot and cold air streams to deliver the proper temperature of air to a conditioned space. Variable-air-volume (VAV) systems reduce mixing by varying the volume of cold (and sometimes the hot) air stream, resulting in significant savings. Figure 6 shows cooling and heating energy use versus outdoor air temperature. The small data points are energy use with the CAV system and the large data points are energy use after a CAV to VAV retrofit; both cooling and heating energy use decrease after the retrofit. The energy efficiency of cooling tower systems and many other systems also improves when mixing is minimized or eliminated.

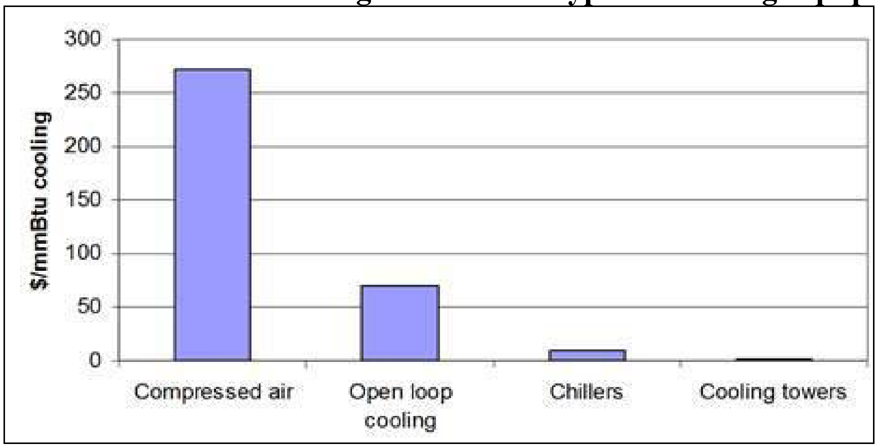
Figure 6. Energy Savings from Reducing Mixing in CAV to VAV Retrofits



Match Energy Source to End Use

The energy efficiencies of energy delivery systems vary widely. Matching the appropriate energy source to the end use can result in significant savings. For example, the energy efficiencies of cooling using compressed air, open-loop water, chillers and cooling towers differ by near orders of magnitude as in Figure 7. If an end use permits cooling with a cooling tower supplying water at 80 F instead of a chiller supplying water at 50 F, energy use can be reduced nearly 10 fold.

Figure 7. Cost Per Unit Cooling of Different Types of Cooling Equipment



Benchmark Against Minimum Energy Use

Always ask "how much energy is really required?" The answer is often "much, much less than is being used". For example, a famous study by Ayers (Ayers 1989) estimated that only 2.5% of primary energy is used to provide energy services in the U.S. Calculating or estimating the minimum energy use required to accomplish a task is often an excellent way to conceptualize more energy efficient processes.

Consider for example the ultra violet (UV) radiation curing oven shown below. Quick calculations showed that less than 0.14% of UV radiation was actually hitting a part with ink that needed to be cured as listed in Figure 8. This observation led to a recommendation to slow the belt and reduce the number of UV lamps that subsequently reduced energy use by 50%.

Figure 8. UV Curing Oven and UV Light Breakdown

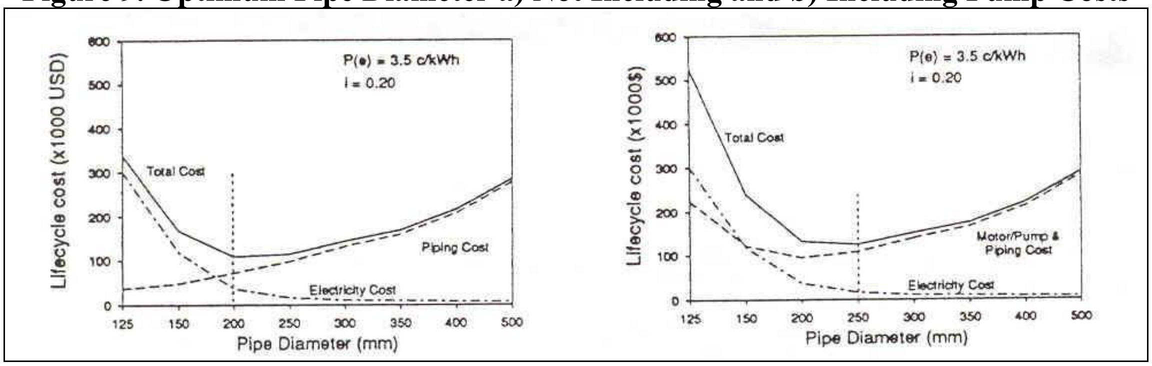
End Use	% Total
Light hitting conveyor belt	99.23%
Light hitting non-inked part	0.60%
Non-UV light hitting inked part	0.06%
UV light hitting inked part	0.14%
Total	100%

Consider Whole Systems Over Whole Time Frames

In nature, no single tree is optimum for all environments. From an evolutionary perspective, 'optimum' is synonymous with 'perfectly integrated' within a system. Thus, when seeking engineering optimums, it is important to consider the whole system over the whole time frame of the device. In engineering this is called life-cycle analysis (LCA). LCA considers purchase, operating, and end-of-life costs using a consistent methodology.

Failure to use LCA generally leads to non-optimal designs that use excess energy. For example, a two-year simple payback threshold for energy investments frequently eliminates many investments that would pay back and save energy over the 10 to 20 year lifetimes of the machines. Similarly, defining the system boundary too narrowly generally leads to sub-optimal designs. Consider for example, the task of determining the economic optimum pipe diameter in a pumping system. As shown in Figure 9, when a pumping system was defined as the cost of the piping and pumping energy, the optimum pipe diameter was determined to be 200 mm. However, when the pumping system was defined as the cost of the piping, pump and pumping energy, the optimum pipe diameter was determined to be 250 mm (Larson & Nilsson 1991). Considering the “whole system” resulted in 50% less pumping energy.

Figure 9. Optimum Pipe Diameter a) Not Including and b) Including Pump Costs

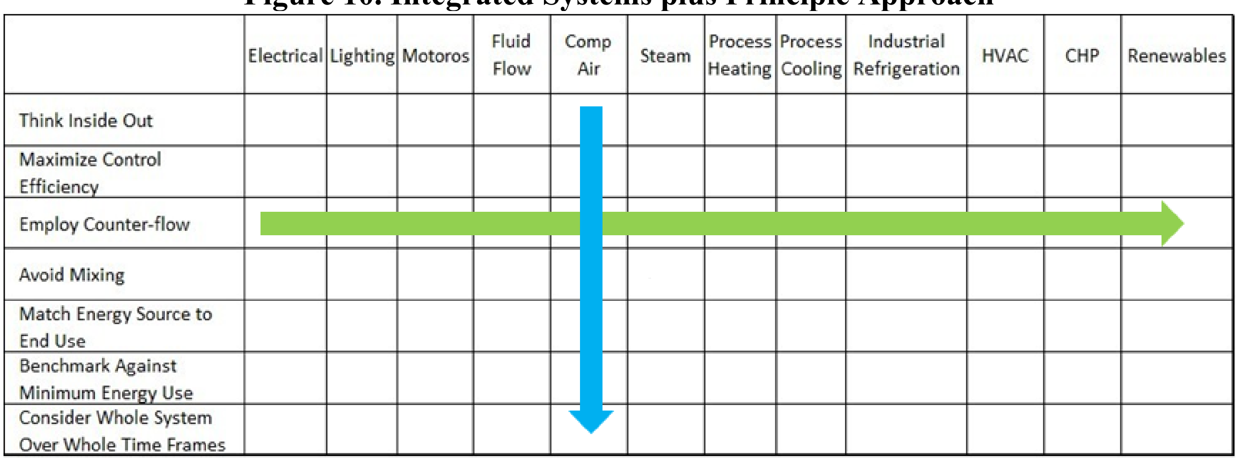


Source: Larson & Nilsson 1991

Integrated Systems Plus Principles Approach

The application of these principles of energy efficiency to the energy using systems described above results in a thorough analysis of the energy saving potential. Figure 10 illustrates the process for applying ISPA to manufacturing plants to identify energy savings.

Figure 10. Integrated Systems plus Principle Approach



The application of these principles to energy systems can also lead to a checklist of best practices for each energy system. These best practice checklists can then serve as a thorough and teachable guide for identifying energy saving opportunities. The checklist can also reinforce the importance of existing best practices and guide decisions about future energy systems. When

ISPA is used in this manner, the energy assessment process is transformed for both auditors and clients.

To illustrate the benefits of ISPA, consider a non-ISPA based energy audit. Energy audits have been a staple in the energy efficiency business for decades, and are proven effective. However, without ISPA, auditors must develop expertise with many manufacturing processes rather than with just a few energy systems. The energy saving opportunities identified are largely dependent on the previous experience of the auditor. Further, even with previous experience, auditors can forget energy saving opportunities while on site. Finally, the list of energy saving opportunities delivered to the client generally leaves the client with no better understanding of how to efficiently operate their existing energy systems or how to proceed if energy systems are modified or added.

In contrast, an ISPA-based energy assessment organized around energy systems and including principles of energy efficiency and system best practices provides both auditor and clients with a thorough, coherent and repeatable approach that identifies saving opportunities, reinforces best practices, and guides future decision making. On every UD-IAC audit, ISPA is applied by the engineering team and taught to plant personnel. Once the plant personnel understand the methodology, they are no longer simply the client, but a member of the audit team. Armed with the Energy Efficiency Guidebook described in a following section, trained plant staff can continue to quantify and justify energy savings projects, replicate savings in sister plants and conduct corporate-level training sessions. Thus, ISPA leads to increased implementation of projects and continuous improvement.

Teaching Energy Efficient Manufacturing Using ISPA

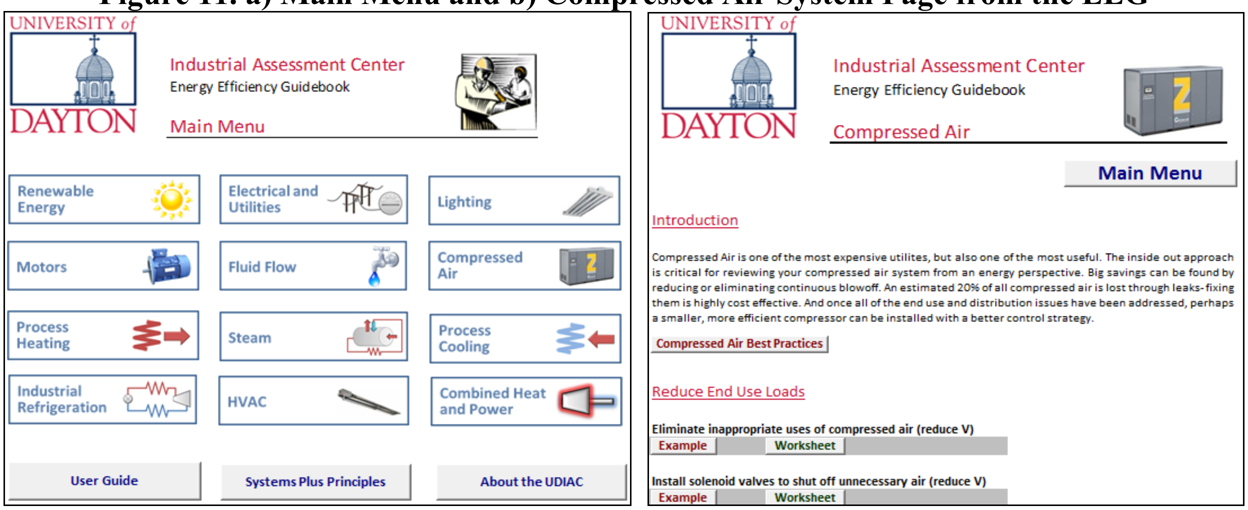
In virtually all scenarios for stabilizing climate, improving energy efficiency is targeted as the primary method. In order to meet carbon emission reduction goals, the rate of energy efficiency improvement will have to increase dramatically. Increasing the rate of change will require changes in social, economic and political systems. It will also require that energy efficiency is specifically addressed in engineering education. The current method of implicitly addressing energy efficiency in the context of existing courses on thermodynamics, fluid mechanics, heat transfer, etc., will not enable students to understand the advanced techniques and applications needed to accelerate the rate of energy efficiency improvement.

The ISPA method provides a coherent and teachable structure for teaching energy efficiency in dedicated engineering courses. For example, the method has been used with success in teaching senior and graduate level courses in Energy Efficient Manufacturing at the University of Dayton. Energy Efficient Manufacturing is wholly structured on ISPA. Principles of energy efficiency are introduced early and illustrated with several examples. The course then proceeds through each energy system. Each energy system begins with an energy balance that connects energy input to end use energy and energy losses. The energy balance equation provides a guide to energy efficiency opportunities by specifically identifying energy losses. Proceeding from “inside out”, specific opportunities for improving the energy efficiency of each system by reducing these losses are discussed and illustrated with example calculations. Applications of the principles of energy efficiency are reinforced throughout the course with examples in each energy system. Students rate the course highly and use it a launching pad and reference for careers in energy efficiency.

The Energy Efficiency Guidebook

While the ISPA provides a clear method to identifying savings opportunities, practitioners still face the significant task of quantifying energy savings to determine whether or not to invest in a particular measure. Realizing significant energy and carbon savings depends on the accuracy and repeatability of these results, the UD-IAC has developed an open-source, public domain, comprehensive resource for teaching and implementing the fundamentals of industrial energy efficiency. The Energy Efficiency Guidebook (EEG) puts powerful tools to identify and quantify energy savings opportunities in the hands of manufacturers, energy consultants, and students. Figure 11a shows the main menu of the EEG and Figure 11b shows the opening page for the compressed air system.

Figure 11. a) Main Menu and b) Compressed Air System Page from the EEG



Following ISPA, the EEG is divided into twelve energy systems. Each system page has links to system best practices and case study examples. System best practices are derived from principles of energy efficiency and provide a guide to common energy efficiency opportunities. The case study examples are selected from hundreds of industrial energy efficiency recommendations for clarity, quality, and frequency of occurrence. The examples are presented according to the "Think Inside Out" principle, in the order of end use, distribution, and then energy conversion. Each case study contains a thorough description and engineering analysis of the opportunity, the resulting calculated energy and carbon savings, and basic economic analysis. Each case study also links to calculation spreadsheets and/or energy simulation software to quantify savings.

Conclusion

Improving energy efficiency is widely considered to be the single most cost-effective and important method climate stabilization. In order to meet carbon emission reduction goals, the rate of energy efficiency improvement will have to increase dramatically. The Integrated Systems plus Principles Approach to energy efficiency provides a coherent, reproducible and teachable method to improving manufacturing energy efficiency. It has also proven to be highly cost effective. For example, employing ISPA in the 27 industrial energy assessments conducted by the UD-IAC in 2012, resulted in energy efficiency opportunities that would reduce overall energy use by 13.3% with a return on investment of 64% (assuming 10 year lifetimes of energy savings). Widespread application of ISPA can accelerate these efforts.

Acknowledgements

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