Chapter 31

Toward Energy Efficient Manufacturing Enterprises

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Abstract

Industrial enterprises have significant negative impacts on the global environment. Collectively, from energy consumption to greenhouse gases to solid waste, they are the single largest contributor to a growing number of planet-threatening environmental problems. According to the Department of Energy’s Energy Information Administration, the industrial sector consumes 30 % of the total energy and the transportation sector consumes 29 % of the energy. Considering that a large portion of the transportation energy costs are involved in moving manufactured goods, the energy consumption of the industrial sector could reach nearly 45 % of the total energy costs. Hence, it is very important to improve the energy efficiency of our manufacturing enterprises. In this chapter, we outline several different strategies for improving the energy efficiency in manufacturing enterprises. Energy efficiency can be accomplished though energy savings, improved productivity, new energy generation and the use of enabling technologies. These include reducing energy consumption at the process level, reducing energy consumption at the facilities level, and improving the efficiency of the energy generation and conversion process. The primary focus of this chapter is on process level energy efficiency. We will provide case studies to illustrate process level energy efficiency and the other two strategies.

31.1 Introduction

Companies often find it difficult to obtain needed traction on addressing energy efficiency efforts. Company managers view energy use as a necessary cost for conducting business and they have difficulty in competing energy with other core operational needs [1]. Recent public perception and marketplace pressures have companies taking a second look at energy efficiency within the enterprise and with life cycle considerations. The life cycle of a product can have several beginnings. One such cycle that starts with raw material extraction and processing is shown in Figure 31-1. This cycle continues with the pre-design and fabrication of the relevant semi-finished products, includes manufacturing and assembly of the final product as well as its transportation, use and maintenance, and concludes with the end-of-life operations. This last stage includes recycling of materials and, after adequate treatment, final disposal of waste.

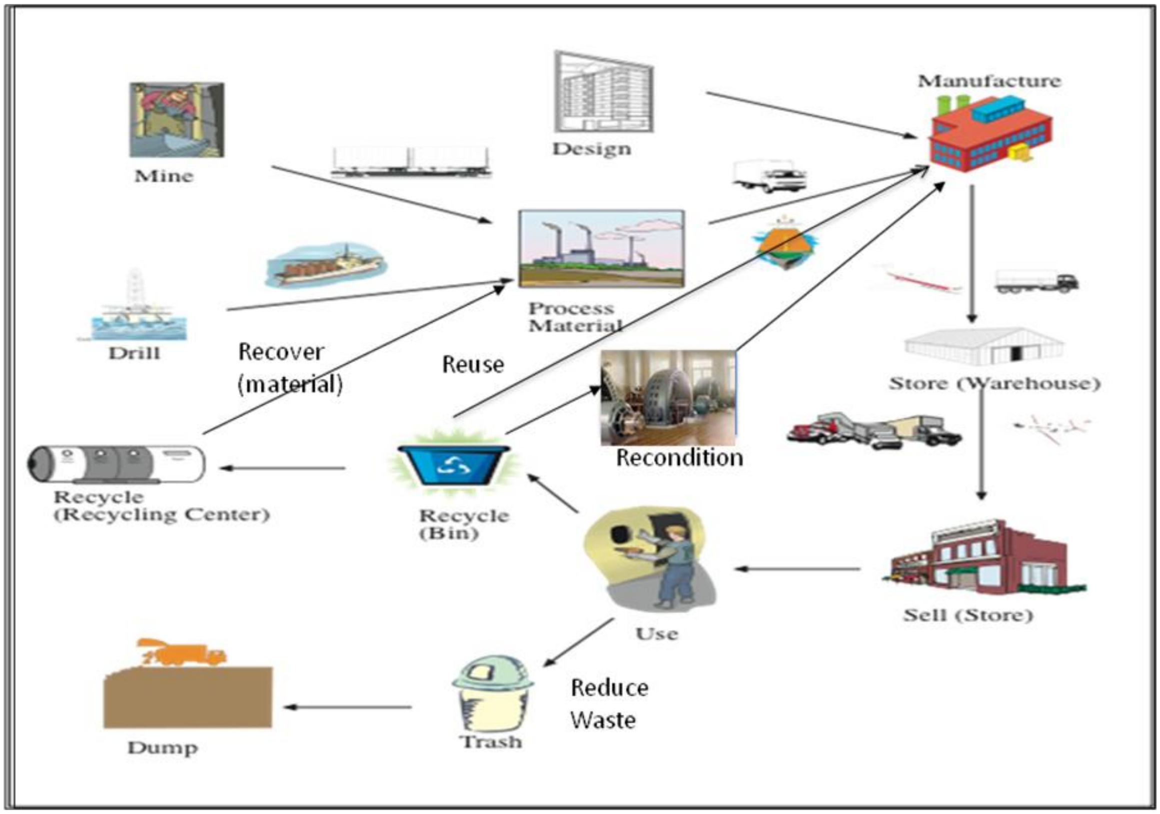


Figure 31-1: Product life cycle: From mining to reuse

A generalized version of this cycle is shown in Figure 31-2. The figure shows two cycles. The first cycle depicts the extraction of material from the Earth and putting waste back into the Earth. We would like to minimize this flow and, in particular, achieve zero landfill. The second cycle includes pre-design, production, use, and post-use stages of the product life cycle. The thick (green) arrows represent material and information flow between these stages. The reverse arrow from use stage to production stage denotes the field data from product use into design and manufacturing to improve the design.

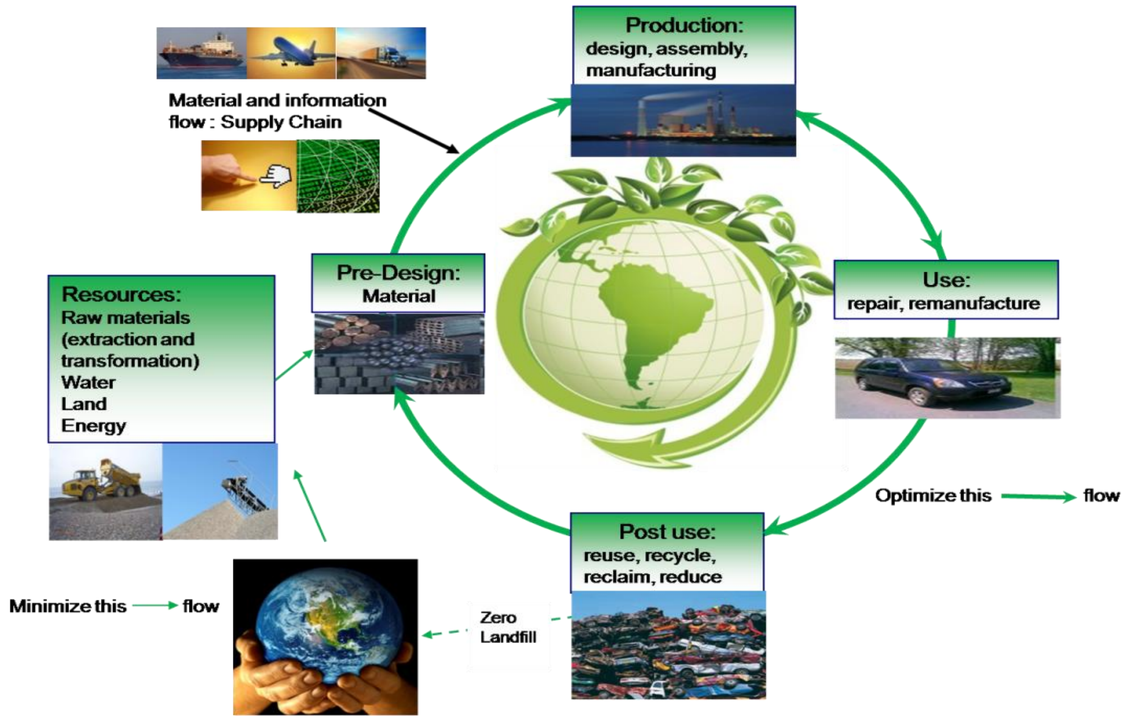


Figure 32-2: A closed loop view of product life cycle and sustainable manufacturing

The various stages in the above product life cycle have a significant impact on the environment. According to a recent report from the University of Cambridge: "the industrial system can account for 30% or more of greenhouse gas generation in industrialised countries" [2]. This statement reflects only a part of the total impact on the environment. Energy consumption and waste production are other major factors that affect the environment. For example, according to the Department of Energy's Energy Information Administration, the industrial sector consumes 31 % of the total energy and the transportation sector consumes 28 % of the energy [3]. Considering that a large portion of the transportation energy costs are involved in moving manufactured goods, the energy consumption in the industrial sector could reach nearly 45 % of the total energy costs. The U.S. Energy Information Administration's Annual Energy Review 2009 provides an excellent source of information for energy consumption in various sectors [4]. It also shows energy flows from source (e.g., coal, hydroelectric power, renewable energies) to a particular sector (e.g., transportation, industry, etc.).

A product's energy life cycle includes all aspects of energy production [5]. Depending on the type of material and the product, energy consumption in certain stages may have a significant impact on the product energy costs. For example, one kilogram of aluminum requires about 12 kilograms of raw materials and consumes 290 MJ of energy [6]. Several different strategies can be used to improve the energy efficiency of manufacturing enterprises, including reducing energy consumption at the process level, reducing energy consumption at the facilities level, and improving the efficiency of the energy generation and conversion process. While the primary focus of this chapter is on process level energy efficiency, we will briefly discuss energy reduction methods and efficient energy generation process through case studies.

Outline of the chapter: A rationale for energy efficient manufacturing is provided in the next section (Section 31.2). The concept of unit manufacturing processes is introduced in Section 31.3, followed by a classification of these processes in Section 31.4. Section 31.5 describes the mechanisms used to determine energy consumption. Improving the efficiency of this energy consumption is the realm of Section 31,6. Several case studies are provided in Sections 31.7—31.9. Section 31.7 presents a case study on improving energy efficiency in injection molding. A case study of various innovations used by a small manufacturer for energy efficient manufacturing is provided in Section 31.8. In Section 31.9 we discuss a specific technique – using supercritical fluids -- that can be effectively used to improve energy efficiency and to improve processes that generate energy from non-traditional sources. Finally, in Section 31.10 we point out how best practices, regulations and standards, can play an important role in increasing energy efficiency.

31.2 Energy Efficient Manufacturing

Energy efficiency efforts and the use of renewal energy sources are essential directions that manufacturing enterprises must take to cope with the current global environmental crises [7]. A manufacturer's energy inputs can be described by the following five progressive stages [5]:

1. ***primary energy input***, which is the total volume of energy assembled to serve industrial needs;
2. ***central generation***, which mainly occurs in powerhouses where fuel is converted to heat and power by a steam plant, power generator or co-generator;
3. ***distribution***, which pipes heat and sends power from central generation to process units;
4. ***energy conversion***, which transforms heat and power to usable work, and involves motors, fans, pumps, and heat exchangers; and
5. ***processes***, where converted energy transforms raw materials and intermediates into final products.

The primary focus of this chapter is on energy conversion and manufacturing processes although aspects of primary energy input, central generation, and distribution are covered when considering life cycle analysis (LCA).

Advanced manufacturing sciences and technologies are necessary to support, promote, and implement energy reduction and renewable efforts. Yet, progress of these efforts is hindered as industry lacks the science-based approaches enabling quantifiable measurement techniques, tools, and data that support objective evaluation of progress against specific aspects of product life cycle. Beyond energy reduction and renewal technologies, manufacturers are starting to look at the entire life cycle of products and services to conserve energy and natural resources, minimize negative environmental impacts, ensure safety for employees, communities, and consumers, and improve economic viability [8].

The U.S. Department of Energy (DoE) and the U.S. Council for Automotive Research (USCAR) created a technology roadmap for energy reduction in automotive manufacturing. The goal of the roadmap is to guide decision-making for future research, development, and demonstration projects through identification of potential ways to reduce energy intensity in automotive manufacturing and the associated supply chain. This report is organized around five major operations within automotive manufacturing [9]: 1) Body in White and Components, 2) Paint, 3) Powertrain and Chassis Components, 4) Final Assembly, and 5) Plant Infrastructure. Through the combined data collection, analysis and reporting of energy consumption occurring within these major operations, USCAR members are able to recognize and take appropriate actions for energy efficiency at the major operation level. Figure 31-3 illustrates the major operations, a description of each operation, the flow of materials between processes, and approximate percent of energy that each process requires of the total enterprise energy. Such flows can be developed for other industries.

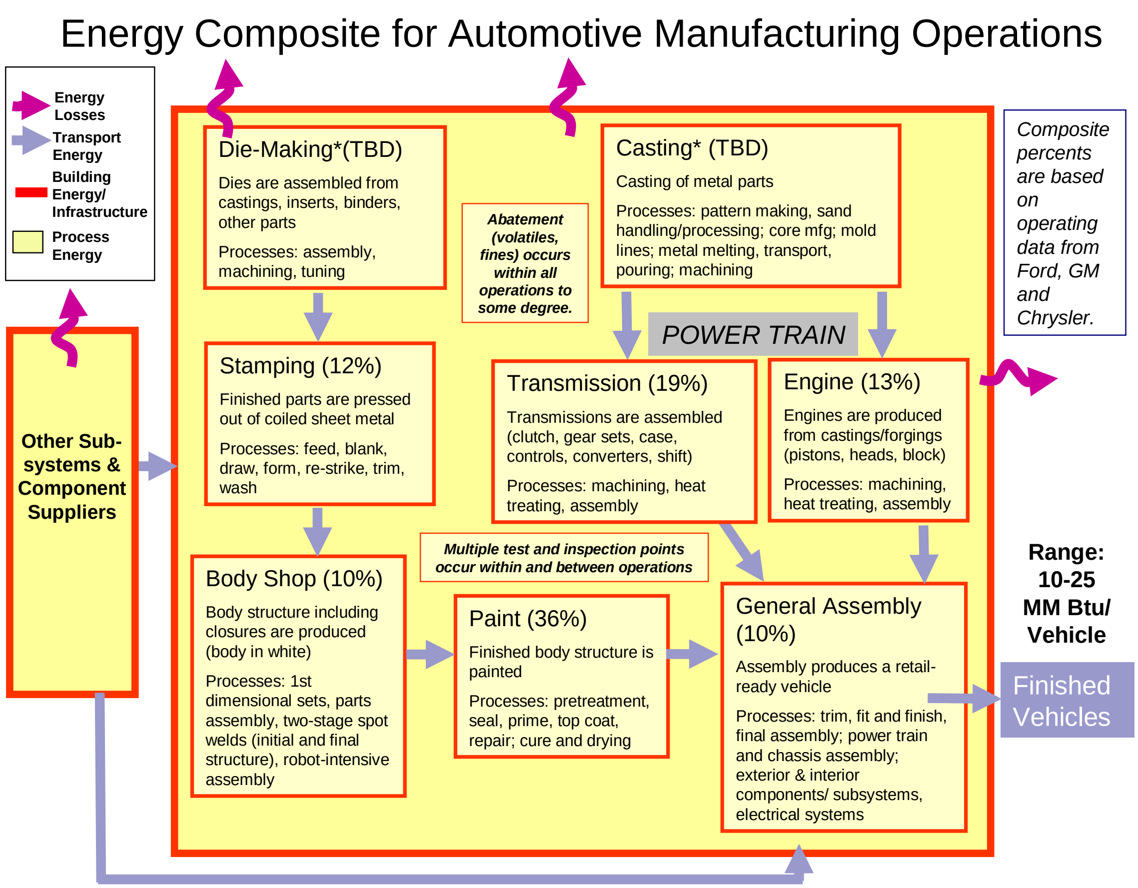


Figure 31-2: Distribution of energy use in Major Operations in a typical automobile manufacturing plant [9]

Companies are challenged to accurately determine energy utilization within a plant or enterprise beyond major manufacturing operations, down to the plant floor equipment level. Companies recognize the need to improve energy efficiency practices yet they lack formal descriptions of resources that promote automation and the development/improvement of tools. As a result, current process improvement efforts are likely to address known, easy to identify problems, potentially failing to address the bigger picture that systems and life cycle approaches would have highlighted. If companies are able to take into account system and life cycle considerations in regards to addressing energy efficiency issues they must identify and evaluate competing performance attributes or tradeoffs. A process improvement may decrease energy consumption at one stage of manufacturing, but increase consumption at another, or increase waste. Similarly, an overall reduction in manufacturing energy consumption may produce a product that requires more energy to operate, or may result in a less durable product that must be replaced more often. For example, a product that takes 5 MJ to manufacture but lasts for 10 years is more energy-friendly than a product that takes 4 MJ to manufacture but only lasts for 5 years (and therefore must be replaced). Analyzing these tradeoffs and using them to make decisions requires detailed, comprehensive models.

31.3 Unit Manufacturing Processes

As stated in Reference [10], manufacturing, reduced to its simplest form, "involves the controlled application of energy to convert raw materials (typically supplied in simple or shapeless forms) into finished products with defined shape, structure, and properties." Joining and assembly operations can also be viewed similarly. The energy applied during the unit manufacturing operations may be mechanical, thermal, electrical, or chemical in nature and sufficient detail is needed to understand the allocation of energy consumption within each unit process.

Unit manufacturing processes are formal descriptions of manufacturing resources at the individual operations level (e.g. casting, machining, forming, surface treatment, joining, and assembly) required to produce finished goods. Engineers have historically evaluated complex systems by breaking them down into smaller and more manageable parts that together still adequately represent the complete system, and are computational tractable. This approach simplifies the difficult task of alternative methods for creating accurate abstractions of a production system.

Unit manufacturing processes provide a science-based methodology for companies to describe their manufacturing resources. This can aid in understanding their production processes and equipment thus enabling process and product performance improvements. By identifying and defining the unit process, engineers gain a better understanding of the production process performance, thus allowing them to identify, analyze, and improve energy efficiency of the unit process and ultimately the enterprise. Initial applications of the unit process methodology include: 1) providing highly reproducible, accurate positioning of production equipment component motions needed to improve precision levels, 2) developing innovative equipment designs that dampen vibrations so that they are not transmitted to the tooling and workpiece, 3) reducing warm-up time from process start-up to operational steady state to attain minimal energy use, and 4) increasing speed of operation -- while achieving consistency of part characteristics, such as dimensional control [10].

The intent of unit processes, and their ultimate utility, is to enable collections of unit processes to define an entire process flow for a component or product. This linking of unit processes, with the output of one process serving as the input for the next process, clearly illustrates the dependency of one process on another for achieving process and product performance. This collection of unit processes also supports calculation of the energy use required to complete specific operations or to produce a product. Unit process models support decisions regarding continuous improvement of the individual unit process as well as the system of unit processes. In addition, social factors such as rapid response to customer needs or having safe working conditions can also be addressed. Over the years, the use of unit process methodologies has achieved most success in the chemical sector.

Enhancements to the unit manufacturing process concept have continued to evolve. To increase their utility there was a need for an innovative methodology to incorporate life cycle considerations into the model. A new methodology called Unit Process Life Cycle Inventory (UPLCI) was developed to use the manufacturing unit process as the basis for life cycle inventory [11]. UPLCI involves the 1) preparation of a process description that includes appropriate supporting information for describing value-add steps, and 2) the development of process mass loss equations and applicable examples that assist users in applying methods to their work, and references to supporting equations and data. The UPLCI model is further refined through the study of four types of data: 1) time, 2) power, 3) consumables, and 4) emissions [11]. Whereas the initial unit process model applications could be quite complex, UPLCI model development looks for simplicity and tries to minimize information or excessive rigor in deriving estimated energy consumption to maximize productivity and promote wider acceptance of the methodology by industry.

31.4 Categorization of Manufacturing Processes

There are hundreds of unit manufacturing processes. These processes share common traits that define a taxonomy. Taxonomies provide structure that supports systematic categorization which facilitates search and retrieval operations. One approach to taxonomy construction is to arrange various manufacturing processes according to function [12] while another approach can be descriptive headings that alert companies of expected energy types and use. In all cases, taxonomies add structure and systematic categorization facilitates search and retrieval operations. This allows companies to rapidly locate a generalized description of a particular manufacturing process that can serve as the foundation for the company's unique instantiation. Listed below are two widely adopted manufacturing taxonomies:

1. Allen and Todd's manufacturing processes reference guide [13]. (See Figure 31-4.)

2. CO2PE! – "initiative process taxonomy based on the German standard DIN 8580 (Fertigungsverfahren - Begriffe, Einteilung) and extended with some auxiliary processes like compressed air supply, cooling systems, etc. [14]"

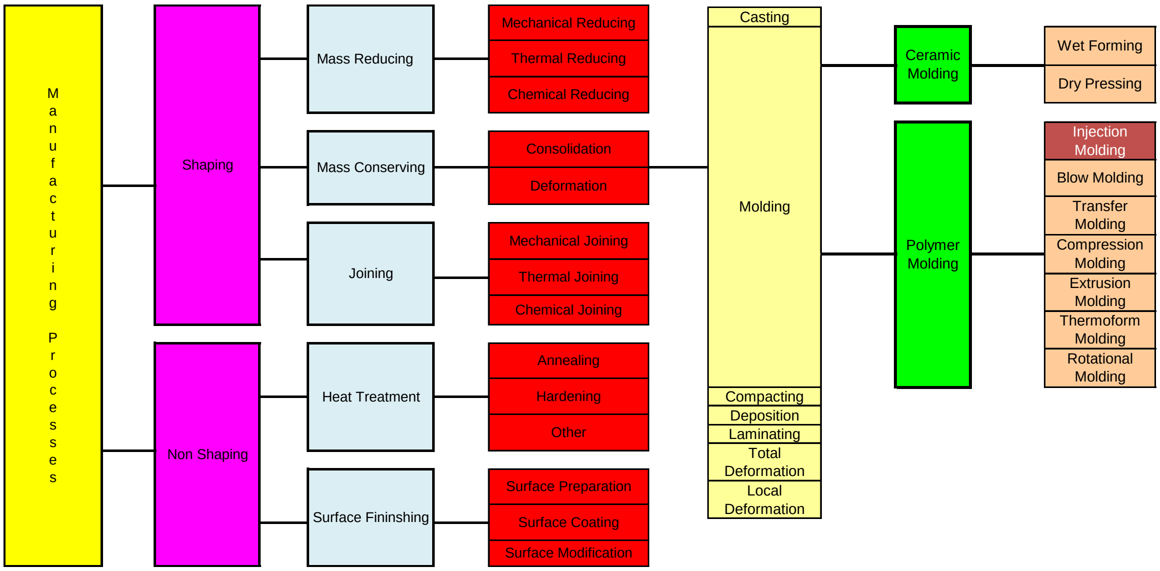


Figure 31-3: Partial taxonomy (Allen and Todd) to highlight injection molding process [13]

Another set of descriptive categories was proposed by a National Research Council (NRC) study group [10]. This top-level taxonomy organizes all processes into the five descriptive categories listed below.

1. ***mass-change processes***, which remove or add material by mechanical, electrical, or chemical means (included are the traditional processes of machining, grinding, shearing, and plating, as well as such nontraditional processes as water jet, electro-discharge and electrochemical machining);
2. ***phase-change processes***, which produce a solid part from material originally in the liquid or vapor phase (typical examples are the casting of metals, the manufacture of composites by infiltration, and injection molding of polymers);
3. ***structure-change processes***, which alter the microstructure of a workpiece, either throughout its bulk or in a localized area such as its surface (shot peen stress relief, heat treatment and surface hardening are typical processes within this family; the family also encompasses phase changes in the solid state, such as precipitation hardening);
4. ***deformation processes***, which alter the shape of a solid workpiece without changing its mass or composition (classical bulk-forming metalworking processes of rolling and forging are in this category, shot-peen forming, as are sheet-forming processes such as deep drawing and ironing); and
5. ***consolidation processes***, which combine materials such as particles, filaments, or solid sections to form a solid part or component (powder metallurgy, ceramic molding, and polymer-matrix composite pressing are examples, as are *permanent* joining processes, such as welding and brazing).

The NRC report also suggested a sixth category that recognized the likelihood of innovative configurations of unit processes.

6. ***integrated processes***, which combine more than one specific unit process into a single piece of equipment or into a group of work stations that are operated under unified control.

31.5 Determining Energy Consumption

A product's energy life cycle describes its total energy impact, including all stages of its manufacture through the end of its operating life and includes its eventual disposal [5]. This is referred to as cradle-to-grave analysis that captures relevant sustainability data starting with the extraction of raw materials and accounting for all operations until the final disposal of these materials. The total energy should reflect the collective contributions of life cycle factors (such as embodied energy in raw materials, scrap, and disposal) and in-direct manufacturing activities (such as transportation of materials, product packaging, and HVAC).

To determine energy consumption rates at the unit process level requires specific knowledge of the production process (resource inputs, outputs) and the measurement methodology necessary to support reporting and decision support requirements. Typically there are a number of possible methods that can be used to measure energy rates. Each of the methods is based on various assumptions and data that result in specific precision and accuracy. They also have different costs, depending on the physical and software resources required to take the measurements, the time to take the measurements, the maintenance for continuous operation, and the time for reducing and formatting the data for reporting and decision support. There are new advances in acquiring data from manufacturing processes that make it easier for companies to collect critical measurement data for assessing energy consumption and other sustainability data [15].

A growing number of companies have installed and begun to use Energy Management Systems (EMS) that provide monitoring and reporting capabilities at a sub-station or possibly at the major operation level. Facets of energy management have a notable common requirement: the need for advanced data collection and analytical tools that facilitate energy-efficient practices [16]. Table 31-1 describes some data sources that companies should explore for determining their energy management requirements.

Data Source	**Data Description**
Energy Management Control System Data (EMCS)	Building data from automation systems, HVAC, lighting systems, boiler, chiller, turbine, and other equipment
Energy Meter Data	Data from energy meters and submeters, which can include electricity, chilled water, steam, gas, fuel, water and other metered resources
Enterprise Resource Planning (ERP)	Enterprise-level business data, such as supply-chain, asset, financial, project and others
Data Historian	A historical data repository that efficiently stores data from manufacturing process, facility metered, or other types of historical data
Weather Data	Temperature, pressure, humidity, and other weather data

Building Data	Building type, design specifications, and square-footage data
Web Data	Various internet data sources such as DOE or EIA energy databases or forecasted weather data
Billing Data	Incoming and outgoing utility billing data, which may also come from the ERP system
Scheduling Data	Line schedules, room schedules, facilities schedules, personnel schedules and others
Excel Data	Historical spreadsheets and reports of Excel data

Table 31-1: Data sources for energy management [16]

When direct energy consumption data is unavailable, an estimate may be made instead. This may be done when it is desirable to make a prediction of energy consumption before manufacturing processes have been designed and implemented. Often times, this is done using an allocation scheme based on specific energy consumption (SEC) [17]. SEC is defined as the amount of energy used by a specific process for a unit quantity of material. Often times, the mass of a part, which can be obtained from a CAD model, is multiplied by the SEC for the given material, which can be found in an LCA database. From this calculation, an estimate of energy consumption is obtained.

We will illustrate the above concept through an example of an estimation for the energy cost of an injection-molded part using this technique is shown in Figure 31-5.

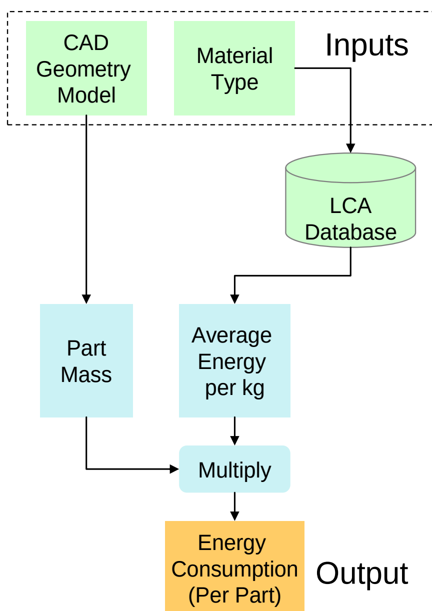
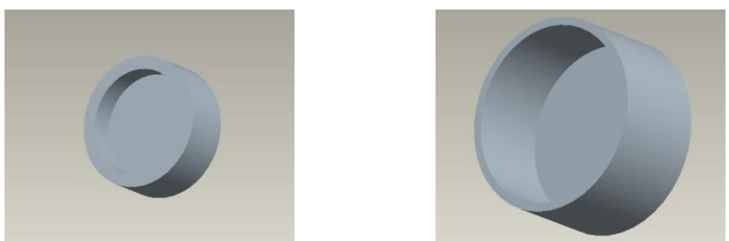


Figure 31-5: Current method used to inventory energy consumption for injection molding

Unfortunately, the available LCA databases only provide an average over the range of machines used in injection molding. This is inadequate because properties of the specific machine used dramatically influence energy consumption. Larger machines require more thermal energy to maintain the polymer temperature, and more power to move the heavier injection and clamping mechanisms. These generalizations lead to wildly inaccurate energy estimates.

In addition, the allocation scheme based on SEC and part mass do not account for the influence of part geometry and cycle time. Parts having the same volume and therefore the same mass, but different geometry can have significantly different cycle times and therefore require different amounts of energy to manufacture. For example, let us consider the two injection-molded parts shown in Figure 31-6. Both parts are made using the same material and have the same volume and mass. However, the maximum wall thickness of the smaller, more compact part (a) is twice that of the larger, thinner part (b). The cooling time for an injection molded part is proportional to the square of the maximum wall thickness [18]. Therefore the cooling time for the cup in Figure 31-6 (a) will be approximately 4 times that of the cup in Figure 31-6 (b). During the cooling time, the machine is idle and continues to consume energy. Therefore increased cooling time, along with increased cycle time of the operation, also results in increased energy consumption. Studies by Gutowski [19] and Krishnan [20, 21] show that the energy consumed by overhead operations such as maintaining the polymer melt and the mold temperature along with pumping fluids and coolants, can be more than the energy used during each production run. Thick parts may especially require active cooling, which requires use of even more energy to supply coolants.



(a) (b)

Figure 31-6: Two different parts with equal volume but different wall thicknesses and cooling times. Part (a) has a wall thickness of 0.05 in., while part (b) has a wall thickness of 0.025 in. Both parts have a volume of 3.34 in^3.

Gutowski and Krishnan [19-21] have shown that machines with a typically higher throughput tend to consume less energy per part. This can be explained by the influence that cycle time has on energy consumption as described above. Since the baseline idling energy is relatively constant, a machine having lower typical cycle times allocates less idling energy per part.

To account for the effects of baseline idling energy, Gutowski divides the specific energy consumption into two components: one component represents the energy used while the machine is idle, and the second component represents the additional energy used to process each unit of material. However, this method still does not account for the variations in power consumption at different stages of the molding cycle. A 2007 study [22] investigating the effects of conformal cooling channels on energy consumption showed that a 40% reduction in cycle time for the same part on the same machine results in only a 20% reduction in energy consumption. This suggests that the portion of the cycle that was shortened consumed power at a rate lower than the average for the entire molding cycle. Therefore, an approach that accounts for a specific part geometry and machine at each stage of the molding cycle could help to achieve a more accurate estimate of energy consumption.

The arrangement of immediate production processes (molding, assembly, finishing) to meet a production schedule can have a dramatic influence on energy consumption in manufacturing processes. This influence is commonly known as energy efficiency [23-25], which is summarized by Kumara as: "Energy efficiency mainly relates to optimizing the ratio of production output to the energy input for the technical building services (heating and cooling) and production machines [26]." A good model of energy consumption should therefore account for production volume, scheduled and unscheduled maintenance of machines, and the design of the factory, in addition to the energy used during the actual molding process. To determine how this ratio of production to energy input can be optimized, discrete event simulation (DES) can be applied. DES, in combination with LCA data, is one possible approach for analyzing the cause and effect of various scenarios where time, resources, place, and randomness determine the outcome and being sustainable is considered crucial. For such analysis only a few research publications exist: Solding and Petku [27] and Solding and Thollander [28] both describe how DES can be utilized to lessen the electricity consumption for foundries. Ostergren et al. [29] and Johansson et al. [30] describe how DES can be utilized in combination with LCA for quantifying environmental impacts during food production. DES has also been explored for an automobile paint shop [31] but has not yet been explored for injection molding processes.

Several authors have investigated the interconnected roles in various manufacturing processes of geometry, material, equipment, and production policy in energy consumption and waste production over the product's entire life cycle. Often times, this is rolled into the single metric of "embodied energy", which is the total yielded energy used to create and destroy a product throughout its entire lifecycle [32]. This has been used to compare energy costs of milling marble slabs versus marble tiles [33], for example. Embodied energy has also been considered in the context of remanufacturing multi-process products such as engines [34], which are made through die casting followed by machining, and the production of double-glazed windows [35], which are made through the float-glass process and milling. Life cycle analyses of die casting [36, 37] and sand casting [38] have also been performed using embodied energy.

Other authors have examined the relative energy costs of different processes which can be used to make the same product. For example, Cho et al. [39] compare the reduced yielded energy cost of continuous casting with hot extrusion and heat treatment for producing copper wirerods. Other works investigate the relative energy costs of semi-solid forging, traditional forging, and die casting for metal alloys [40, 41].

31.6. Improving Energy Efficiency

Energy efficiency refers to technologies and standard operating procedures (SOPs) that reduce the volume of energy per unit of industrial production or energy intensity which is defined as the amount of energy it takes to produce a dollar of goods [6]. The Department of Energy, Office of Energy Efficiency and Renewable Energy's Industrial Technologies Program (DoE) works to improve the energy intensity of U.S. industry through coordinated research and development, validation, and dissemination of innovative energy efficiency technologies and practices

[42]. DoE figures show that industry can achieve energy reductions of nearly 20% to 30% through procedural, behavior, and cultural changes without capital expenditures. The best metrics for energy efficiency have to be clearly measureable, have goals objectively expressed quantitatively and on a time scale, and have status clearly communicated. These goals may be set at the product design stage, at the manufacturing process level, or an approach that spans both design and manufacturing.

Many companies have already begun to improve energy efficiency on the product level by integrating environmental considerations into their product development processes. This effort has come to be part of a paradigm known as Design for Environment (DfE). DfE is defined as “the systematic consideration of design performance with respect to environmental, health, safety, and sustainability objectives over the full product and process life cycle [43].” Design for Environment goes beyond mere compliance with environmental regulations, in which pollutants are simply cleaned up after manufacturing to the minimum extent required by law. Instead, the potential environmental impact of a product or process *throughout its life cycle* is considered while it is still being designed. This generates value for companies in several ways such as improved public image, safeguarding of resources vital to the company’s continuing productivity, and attenuation of clean-up costs after manufacturing. Often times, a direct savings in energy and resource consumption can be realized as well. Finally, DfE has a trickle-down effect. Companies that demand sustainably sourced materials and components can foster competition between suppliers, no longer just on a basis of cost, but on lower environmental impact as well. Several sets of guidelines for integrating Design for Environment into the design process have been proposed [44-48]. Some of these guidelines have come under criticism [49] because they do not offer a means for quantitatively validating a design decision and ensuring that it does, indeed, result in a net reduction in environmental impact. Therefore, it is clear that quantitative methods for assessing environmental impact are vital if DfE is to be an effective tool.

To improve manufacturing processes and energy efficiencies, companies have at their disposal a number of techniques and tools. Companies that have strong lean and green culture typically have positively positioned their site with regards to energy efficiency. Also, companies that have implemented lean principles use proven methods such as Value Stream Mapping (VSM) to ensure minimum waste and improved efficiencies [1, 50]. A Lean and Energy Toolkit [1] gives guidance on developing an energy planning and management roadmap. This roadmap starts at an initial assessment followed by design process, opportunity evaluation, and implementation phases. This toolkit goes on to state three techniques for measuring or estimating the energy used by production processes: 1) metering, 2) estimating, and 3) energy studies. These techniques have been discussed in Section 31.5.

31.7 Improving Energy Efficiency through Improved Product and Process Design: A Case Study in Injection Molding

To illustrate energy efficiency methods, a plastic injection molding example will be used. Plastics are used in a vast majority of products produced in the U.S. and globally. One of the major manufacturing processes used to process plastics is injection molding. This is illustrated in the taxonomy of Figure 31-3. In order to improve the energy efficiency of manufacturing resources one must understand the process in sufficient detail to identify all aspects on how energy is consumed and how use varies over time during setup and steady state operations. Weissman et al. present a methodology for estimating the energy consumed to injection-mold a part that would enable environmentally conscious decision making during the product design [51]. Table 31-2 conceptually shows that engineering changes can be made to the part design to improve the process energy efficiency without impacting the product functionality.

Design Feature	**Operational impact**	**Energy impact**
Thicker minimum part thickness	Increased cooling time	More energy used while machine idles longer
Larger projected part area	Greater clamping force needed	More energy used by more powerful hydraulic/servo mechanisms
Greater part depth	Longer stroke needed to eject part	More energy needed to operate clamp mechanism for longer
Higher specific heat of material	Higher temperatures needed to melt	More energy needed by heating unit
Better part finish	Additional post-processing steps	Energy consumed by those steps

Table 31-2: Injection molding parameters that impact energy consumption [51]

During injection molding, energy is consumed during the cycles to melt, inject and pressurize the resin, open and close the mold, and pump water for cooling. The energy requirements during filling, cooling, and resetting can be determined from the cycle times and the power profile of the machine. The main environmental concerns associated with injection molding are energy consumption and waste generation (mostly waste resin).

To develop an accurate method for estimating energy consumption for injection molded parts, an algorithm consisting of five steps was formulated [51]. These steps are as follows.

1. Determine a surrogate runner arrangement, and its volume, for the mold.
2. Approximate the parameters of the machine that will be used based on the production requirements.
3. Estimate various components of the cycle time for molding a part.
4. Estimate the number of setup operations based on the delivery schedule.
5. Multiply these times by the appropriate average power used in each stage by the selected machine, and sum to get the total energy consumption.

31.7.1 Surrogate Runner Arrangement

First, the CAD model of the part is analyzed to determine the mold cavity volume. In addition to the volume of the part, the volume of the runner system and sprue must also be considered. The runners and sprue are a system of channels which carry the molten polymer from the injection nozzle to various cavities in the mold. In some parts, especially parts at the small scale, the runner system can be much larger than the part. Hence it is important to carefully select the runner layout for estimating the projected volume of the mold cavity.

Figure 31-7 illustrates eight different sprue/runner layouts for four-cavity molds. These layouts are commonly used layouts which use fishbone and ladder layouts. The most appropriate runner layout is selected based on the critical quality metrics such as shrinkage, shear level, part density, mold machining constraints etc. while optimizing for the cycle time and the overall runner volume. The geometry of the mold and the sprue location also plays a significant role in the selection of the most appropriate runner layout. Considering the complex nature of this problem, manufacturers currently select the most appropriate runner/sprue layout based on their prior experience.

Based on the selected runner layout, the projected area of the runner system and the runner volume can be computed. This information is then used for selecting the machine for completing the injection molding operation.

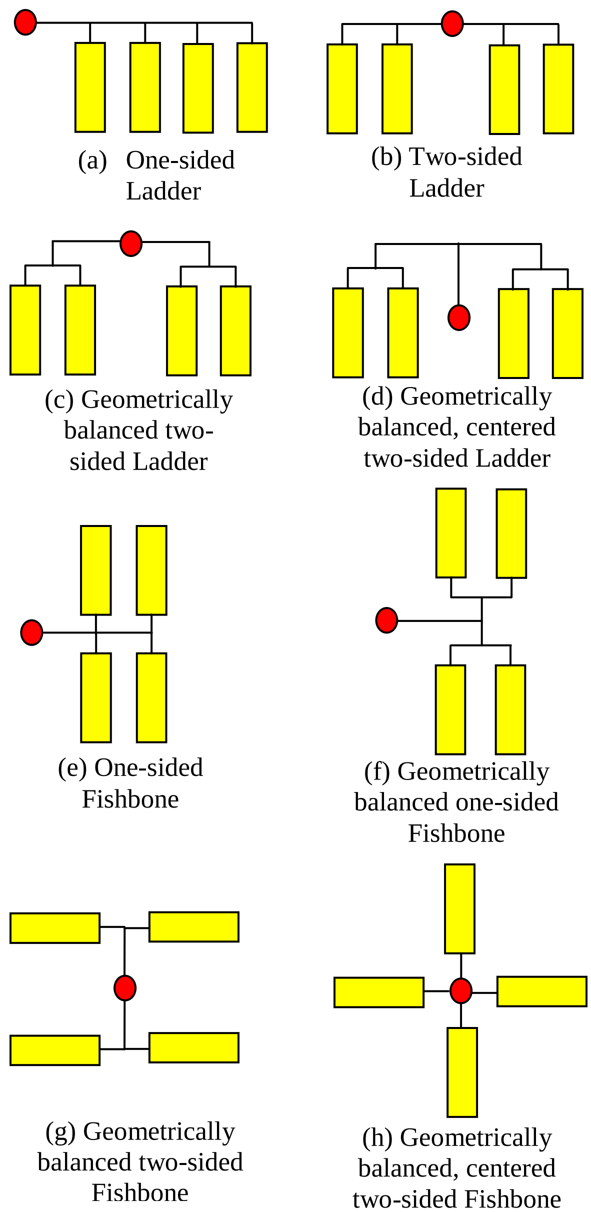


Figure 31-7: Different sprue and runner layout for four-cavity molds [51]

31.7.2 Selection of a Machine

The next step is to estimate the size of the injection molding machine required to mold the part. Machine size is primarily driven by the clamping force required to hold the mold closed during the injection cycle, the shot size required by the volume of the part and runners, and the stroke length required to clear the maximum depth of the part during part ejection. The part volume and maximum depth of the part can be determined from the geometry model. The required clamping force can then be determined from the relationship between the maximum cavity pressure and the projected area of the cavity.

The maximum pressure in the mold can be determined using Moldflow®, given the predicted mold design from the first step and the recommended injection pressure. We then assume that the manufacturer will use the cheapest machine which can provide the necessary clamping force, shot size, and stroke length. The required shot size is equal to the volume of the part, plus the volume of the runners and sprue. The stroke length is typically estimated by a linear relationship with the maximum depth of the part. A machine which meets these criteria can be looked up in a machine database.

31.7.3 Estimation of Cycle Times

Once the machine has been selected, the cycle time for the part is estimated. The molding cycle can be broken down into three stages: injection, packing and cooling, and reset. These stages, as well as their sub-stages and other auxiliary stages in a typical injection molding operation, are shown in the state transition diagram in Figure 31-8.

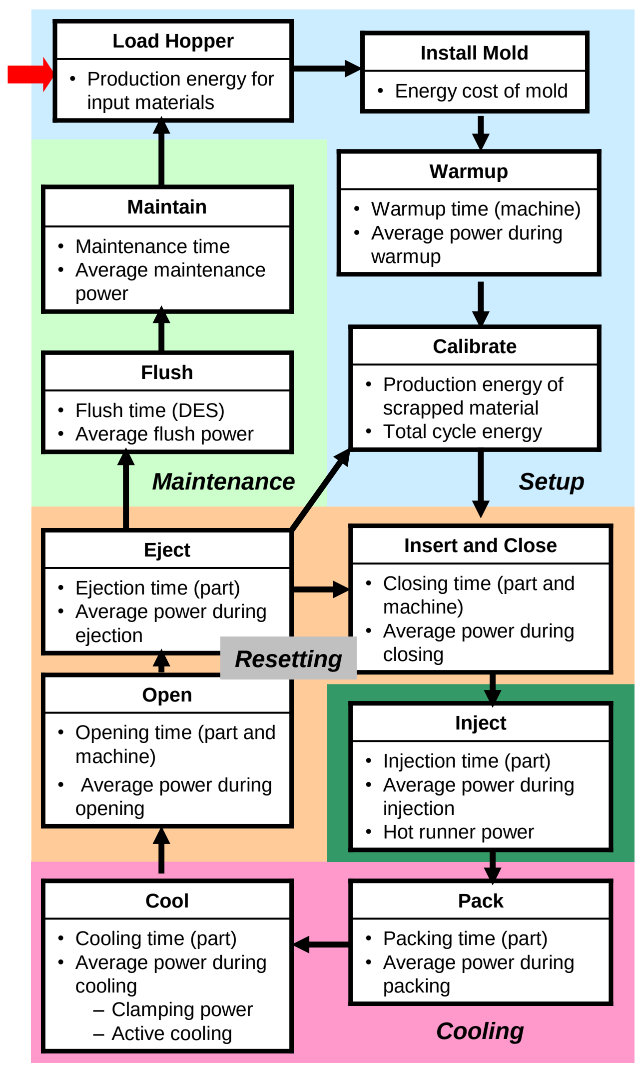


Figure 31-8: Injection molding process – Decomposition of energy consuming states [51]

During the injection stage, the pressure at the injection nozzle is gradually increased. This is done to maintain a constant volumetric flow rate, as the melt cools and solidifies. The estimated fill time for the mold cavity can be derived based on the maximum flow rate. Fill time is approximated as twice the cavity volume, divided by the maximum flow rate of polymer from the nozzle.

Next, the pressure is held and then gradually dropped as the part cools and contracts in the mold. We assumed that active cooling is not used. Using the first term of the Carslaw and Jaeger solution [18], the cooling time in seconds can be estimated from the maximum wall thickness of the part, the thermal diffusivity of the material, the polymer injection temperature, the recommended mold temperature, and the recommended part ejection temperature. The maximum wall thickness can be determined from the part model. The remaining parameters are properties of the material which can be found in the material datasheet provided by the supplier, or derived from those properties. For example, the thermal diffusivity can be computed from the specific heat, thermal conductivity, and density of the material.

Finally, after ejection of the part, the mold is prepared for the next cycle. This time is estimated by applying an overhead to the dry cycle time for the machine. The dry cycle time is typically a measure of the injection molding machine performance that indicates the time for the machine to perform the actions necessary to manufacture a part, without the part actually being produced. The overhead is proportional to the square root of the ratio of the stroke length for our part and the maximum stroke length from the machine.

31.7.4 Estimation of Setup Operations

Before the start of the production, the machine must be set up, which also consumes energy. Setup processes include steps such as warming up the machine, installing the mold, and calibrating the machine. The injection molding machine consumes significant amount of energy during warmup, and then continues to consume energy as it idles during mold installation. Before start of production, the injection molding process needs to be stabilized. This is done to establish process equilibrium to ensure complete filling of the part, avoid jetting, etc. Manufacturers typically reject the first few tens of parts before beginning the production. Therefore the energy consumed during this step is included as part of the machine calibration.

To determine the total energy used during setup processes, it must first be determined how often the machine must be set up during the production schedule of the entire production volume. Typically, the entire production volume will not be completed in a single production run. Typical injection molded parts are produced based on the production requirement and the delivery schedule. The customer specified delivery schedule involves a request for a certain number of parts at regular time intervals. Thus, to save on the inventory cost before delivery to the customer, the manufacturer makes parts in batches. The batch size should be larger than the number of parts delivery requirement at each time interval. Therefore, any remaining parts must be stored at the expense of the manufacturer until the next delivery. However, larger batch sizes require fewer setups. Therefore, there is a tradeoff between the setup cost and the inventory cost. Figure 31-9 shows the relationship between the delivery schedule and the production schedule over the entire production volume. The manufacturer produces a certain number of parts, and delivers to the customer at regular intervals. During this time, undelivered parts remain in storage. When the parts in storage have been depleted, the manufacturer makes a new batch of parts, and continues to ship them out according to the customer's delivery schedule, typically a regular interval of time.

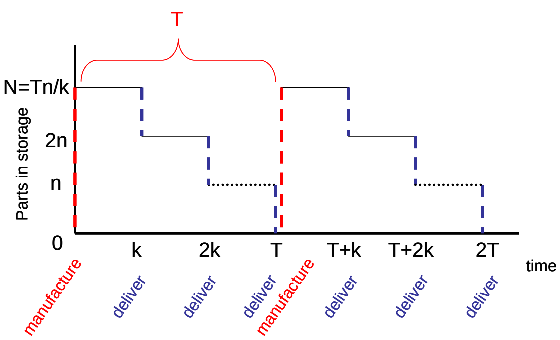


Figure 31-9: Graph showing delivery schedule and production schedule in terms of parts in storage versus time [51]

The tradeoff can be formulated as a single variable optimization problem. The solution to this problem is the optimal number of setup operations which minimize the cost to the manufacturer over the entire production volume. For this problem, it is assumed that the batch production period is much larger than the delivery period, and so lead time can be ignored. Furthermore, it is assumed that the manufacturer must pay for a constant amount of storage; even as the manufacturer's inventory is depleted, they must continue to pay for the entire space needed to accommodate a batch of parts.

The solution to the optimization problem shows that the batch period which minimizes cost is a function of the delivery period *k*, the delivery volume *n*, and the unit costs associated with machine setup and part storage. Together with the total production volume, the optimal number of batches can then be found.

31.7.5 Computing Total Energy Consumption

The energy used during filling, cooling, and resetting can be determined from the cycle times and the power profile of the machine. Assuming that energy consumption per unit of time on a given machine is constant for a given stage of the cycle, the power required, in watts, during each stage can be looked up. Multiplying the power consumed at each stage by that stage's estimated time, and then dividing by the number of mold cavities, the total energy at each stage is computed. Energy used in these stages can be added up to arrive at a total manufacturing energy cost.

This specific example of energy consumption during injection molding that is shown in Figure 31-8 does not reflect a complete life cycle analysis (LCA), as the embodied energy of the raw material, transportation, product use, and recycling/disposal energy contribution was not included. Such challenges for various unit manufacturing processes should be undertaken in the future.

31.8 Reducing Energy Consumption at the Manufacturing Facility: A Case Study at HARBEC Plastics, Inc.

Bob Bechtold is the CEO of HARBEC Plastics, Inc. and is an innovator in implementing sustainable manufacturing practices [52]. His company, which makes high quality injection-molded parts, has made a considerable commitment to being green. HARBEC Plastics Inc. disproved a common misconception that "Being green is nice but we can't afford it" through eco-economic factors implemented at HARBEC. For example, the CHP (combined heat and power) micro-turbines, which are capable of generating 100 % of HARBEC power requirements, provide air conditioning and heat for an injection molding facility, while grid connection provides appropriate back up. HARBEC's air-conditioning system, which uses an absorption chiller, turns exhaust gas waste heat into free air conditioning.

In the area of renewable energy, HARBEC installed a 250 kW wind generator to accomplish wind/microturbine hybrid electricity generation. The projected energy production is 300,000 to 350,000 kWH per year, or about 20 % of the total HARBEC annual energy requirements.

HARBEC, over a seven-year time span, replaced all standard hydraulic type equipment with all-electric injection molding machines. The advantage of electric machines is that these machines do not use power when they are in a static state, which is a significant portion of the time; the machines are capable of doing the same or a better job than the hydraulic machines, using as much as 50 % less energy.

In the area of lighting, HARBEC replaced every fixture, ballast, and high bay sodium lamps with new T-8 type fluorescent bulbs and reflectors. These sustainable manufacturing practices allowed HARBEC to ensure that the lighting energy consumed was reduced by 48 % on average company-wide. HARBEC is a big proponent of LEED, although not LEED (Leadership in Energy and Environmental Design) certified, HARBEC implemented LEED principles wherever it could.

HARBEC has significantly improved their water treatment system by installing a bi-metallic water treatment plant, which does not require any chemicals for water treatment. This enabled them to save thousands of dollars per year on chemicals, and eliminated the need for people to handle them. This new water treatment plant provided 850,000 gallons of fresh water input to their pond, which in turn provides water capacity sufficient for their sprinkler system, and also provides cooling. In a talk at NIST, Bob Bechtold emphasized the overall lesson learned: "*If you want to make an environmental impact, and save money, use energy efficiently.*"

31.9 Improving Efficiency of Energy Generation and Conversion with Emerging Technologies: A Case Study in Use of Supercritical Fluids at Thar Technologies

Emerging technologies provide one way to apply new technology to reduce or remove energy inefficiencies associated with older technologies. New technologies may improve the efficiency of energy generation, or decrease the energy loss associated with converting matter from one phase to another. One example of an emerging technology that can be used to improve efficiency on many different facets is supercritical fluids.

Supercritical fluids (SCFs) exist at temperatures and pressures above the critical point, where the differences between gas and liquid states lose their significance. Various physical properties such as density and dielectric constant change rapidly with pressure and enthalpy and are to some extent “tunable”; i.e., they can be manipulated to achieve a processing goal. Such fluids have a variety of energy efficient applications in solvent extraction, laboratory analysis and heat transfer.

Supercritical fluid extraction (SFE) offers multiple advantages compared to traditional extraction technologies such as organic-solvent extraction or distillation. With SFE there is no residual solvent in either the extract or in the raffinate. This translates into lower operating costs because of the reduction in post-processing steps, clean-up and safety measures. Products extracted with SFE deliver the most natural aromas and flavors because the volatile compounds are not removed as they are in a post-processing step to remove residual solvent. SFE works at low temperatures, resulting in is less deterioration of thermally-labile components in the extracts. Since there is no oxygen in the process, the potential for oxidation of the extract is significantly reduces. Supercritical fluids – particularly carbon dioxide ($scCO_2$) – have application in the production or recovery of alternative energy. Several examples of $scCO_2$’s use are provided below.

31.9.1 Food and fuel: Biodiesel with a Food-production Bonus

Even though the ability of SFE with carbon dioxide to separate triglycerides from oil seeds is well understood and practiced, several technological problems inhibit the development of a continuous, “green” version of this biofuel process. To date, all known extraction of oils or herbal essences using SFE has been performed with batch processing. Fuel production, expected to occur at feed volumes 10-100 times greater than those used in typical herbal extract facilities, demands continuous processing. Various groups have worked on continuous or semi-continuous systems but none has succeeded for a variety of reasons, such as leakages due to carbon dioxide’s low viscosity and the sealing of rotating or linear devices under high pressure. Also, the conventional method of cycling CO_2 through a large pressure range of approximately 700 bar – for the purpose of changing the dissolving characteristics of the solvent – imposes an energy burden on the process.

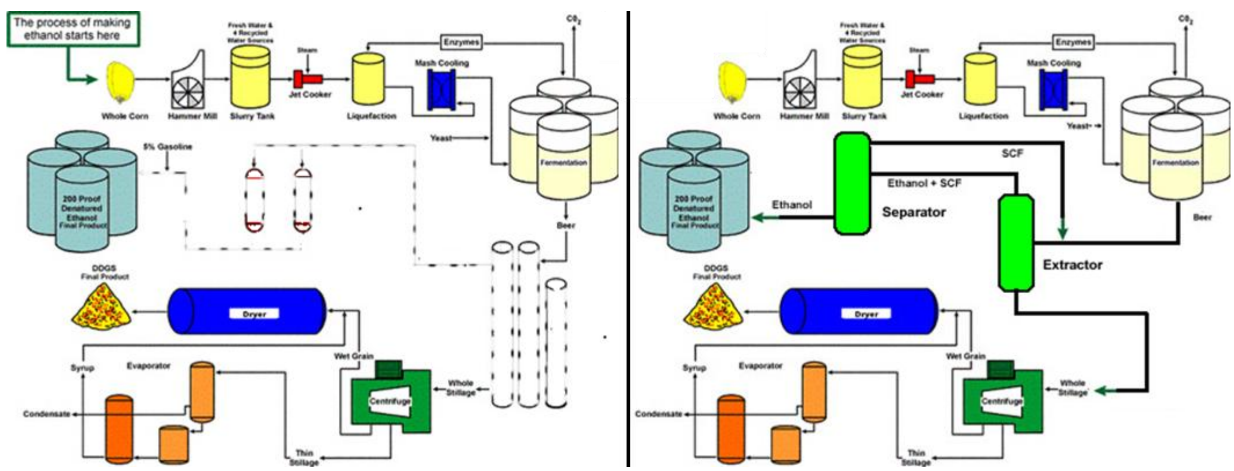
Depending on the feedstock, valuable solid co-products, from high-volume animal feed to low-volume, premium-priced de-fatted soy flour, could also be made using SFE. Byproducts include glycerol and soybean hulls (used in animal feed). This process also offers significant environmental advantages. Current biodiesel processing involves the extraction of oil from soybeans by hexane, a hazardous air pollutant (HAP) according to the U.S. Environmental Protection Agency (EPA). SFE processing eliminates two major sources of pollution from conventional hexane-extraction plants:

1. *Fugitive hexane solvent* itself, which shows up mainly in air emissions, as well as in the meal byproduct that is sold as animal feed.

2. *Solid and aqueous waste products* resulting from de-gumming, de-colorization and de-odorization, which are downstream processes of hexane extraction. Some of the byproducts, such as lecithin, are valuable and can be recovered and re-sold.

31.9.2 Ethanol Extraction

Supercritical fluid extraction of ethanol from aqueous fermentation broth holds promise as a means of cutting the energy consumption that would otherwise go to distillation and subsequent molecular-sieve dehydration. For ethanol derived from corn, distillation and dehydration account for 40 % of the energy input, counting cultivation, harvesting, other processing and distribution. Supercritical fluid extraction could possibly cut this figure to 20 %. The process is, in its simplest rendition, a drop-in replacement of the distillation and de-hydration units, as shown in Figure 31-10.



Original ethanol plant, showing equipment to be replaced (dotted lines)

Revamped ethanol plant, showing drop-in extractor and separator

Figure 31-10: Supercritical fluid replacement for distillation and dehydration in corn ethanol production

This process first separates water from ethanol in a liquid-phase extractor. Then in a lower-pressure gas-phase stripper it condenses the ethanol from the SCF solvent before re-compressing the solvent and returning it to the water separator for a new round of liquid-phase extraction. Sufficient pressure must be maintained in the water separator to guarantee liquid conditions. A temperature gradient is needed across the vertical length of the separator to ensure that water drops to the bottom, while ethanol-rich SCF solvent migrates to the top. The next step of the process, stripping out the ethanol from the solvent, takes place in the gas phase. To do this, latent heat is added in the stripper – mainly by heat exchange with compressed, lean SCF solvent (i.e., depleted of ethanol).

31.9.3 Heating and Cooling using a Natural Refrigerant

Besides its myriad process applications, $scCO_2$, as well as sub-critical CO_2, also act as excellent heat transfer fluids. Carbon dioxide was, in fact, the original refrigerant, dating back more than a century ago. In the first half of the Twentieth Century, it lost out: first to inorganic refrigerants, sulfur dioxide and ammonia; then to organic chlorofluorcarbons in the years just before World War II. But by the end of the century, concern over ozone depletion brought a renewed focus on CO_2, which is environmentally benign and non-toxic.

Supercritical CO_2 has more going for it than environmental advantages. It exhibits unique thermodynamic properties that have only recently gained appreciation. For example, the density of $scCO_2$ is greater than that of gaseous freon by a factor of about seven. This translates to smaller equipment, despite the higher pressure required to contain $scCO_2$. Furthermore, the temperatures of evaporation and condensation for carbon dioxide at sub-critical pressures relate to typical air and ground temperatures in such a way as to open applications in geothermal heat rejection and absorption. In other words, sub-critical carbon dioxide is an attractive geothermal heat-transfer fluid for both heating and cooling.

Geothermal heat-transfer technology involves circulating CO_2 through the ground, to depths typically less than 150 meters. Depending on the mode of operation – cooling or heating – the ground acts as a heat sink to absorb energy (as in cooling) or a heat source to produce energy (as in heating applications). In both cases, the ground temperature is typically 12 centigrade, plus or minus a few degrees, throughout the year. A schematic of this is shown in Figure 31-11. This technology differs substantially from deep underground recovery of heat from superheated sources, such as geysers.

There are actually two modes of cooling, one employing a compressor to move CO_2 in gaseous form and the other relying on a pump to move it in liquid form. A cooling cycle based on liquid pumping satisfies most applications when humidity is already at comfortable levels. For time periods in a day when humidity rises uncomfortably high, the compressed cycle is started in order to condense water from room air. This combination of pumped/compressed cooling is much more efficient than compressed cooling alone. The heating mode is always a compression cycle. In this case, liquid CO_2 is depressurized to 35-40 bar so that it evaporates underground, rather than condensing. Subsequent compression of the evaporated fluid produces temperatures high enough to heat a room. Similar heat-pump systems in use today employ freon-type fluids, but, as noted earlier, gas densities are only one-seventh that of CO_2 and so piping and heat-exchange equipment are much larger.

Numerous variations of the scheme are possible. For example, an existing building with a conventional air-conditioning system that employs freon fluid with air-blown heat rejection can be supplemented with a pumped-cooling geothermal system so as to reduce the energy load overall.

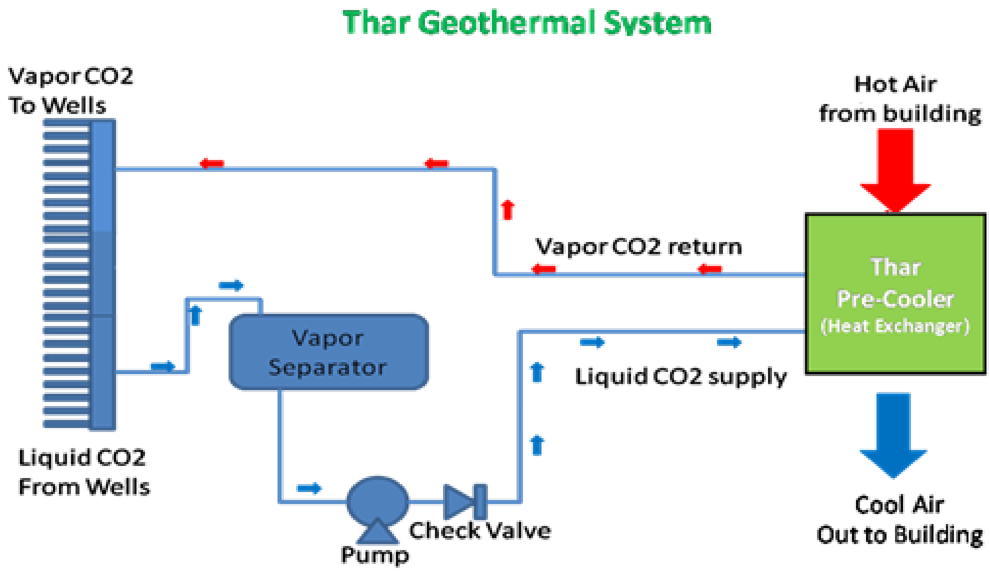


Figure 31-11: Pumped CO_2 cooling system

3.9.3 Miniature Refrigeration Systems

Carbon dioxide has even been tried as the heat transfer fluid for a miniature refrigeration system, small enough to fit inside a desktop computer. One of the co-authors (Lalit Chordia, Thar Technologies) designed and built a small compressor capable of moving enough fluid, at sufficient pressure, to dissipate approximately 100 watts of heat from a computer chip. As part of this effort, Chordia's company also developed a microchannel heat exchanger that came in direct contact with a chip-sized heat source.

Heat exchangers were built with channel widths of less than 100 microns. The channels were open at the edges of a metal foil that was only about 0.3 mm thick. Headers attached to the channeled edges ensured even distribution of fluid either into or out of the foil. Supercritical carbon dioxide is a good choice of a heat-transfer fluid with this type of construction because of its low viscosity. Compared to liquid water, and for the same amount of heat capacity, pressure drop through the channels is one-fifth. Furthermore, carbon dioxide poses less of a hazard in the event of mechanical failure, such as a leak. Thermal resistance, on the other hand, benefits from higher flow rates of supercritical CO_2. Tests conducted by Thar showed that pressure drop would likely exceed 140 kPa in order to achieve resistances of less than the 0.5 C/W. Thus, the use of copper rather than stainless-steel is especially important.

The compressor for this application was a reciprocating type, totally enclosed in a casing that included the motor. This way, there was no possibility of leakage of CO_2 from the crankcase. The entire assembly was small enough to fit in the palm of a hand.

31.9.4 Power Generation using the CO_2 Brayton Cycle

Not all applications for CO_2 as a heat-transfer fluid involve underground operations. One concept captures solar heat in tubes, allowing pressurized fluid to rise to a high enough temperature that heat recovery becomes much more efficient than in conventional water-based systems – and more efficient than photovoltaic systems, for that matter. The same concept can be applied to the recovery of waste heat if such sources exist at temperatures of at least 150 C, which might occur in underground sources starting several hundred meters below the surface.

The cycles shown in Figure 31-12 operate clockwise, starting with staged liquid pumping, with intercooling, to get to a supercritical pressure for heat absorption. In the case of concentrated solar power, energy is absorbed by fluid running through flow channels onto which light is focused. In waste heat recovery, some type of tubular heat exchanger might be employed. Once the fluid is hot enough it is depressurized through a series of turbines to recover energy as electrical power. The fluid coming out of the last turbine is still hot enough to provide substantial pre-heating to the pressurized fluid by means of a recuperator, the thermodynamic boundaries of which are represented in Figure 31-12 by the dotted lines. Just how efficient these cycles can be is shown in Table 31-3.

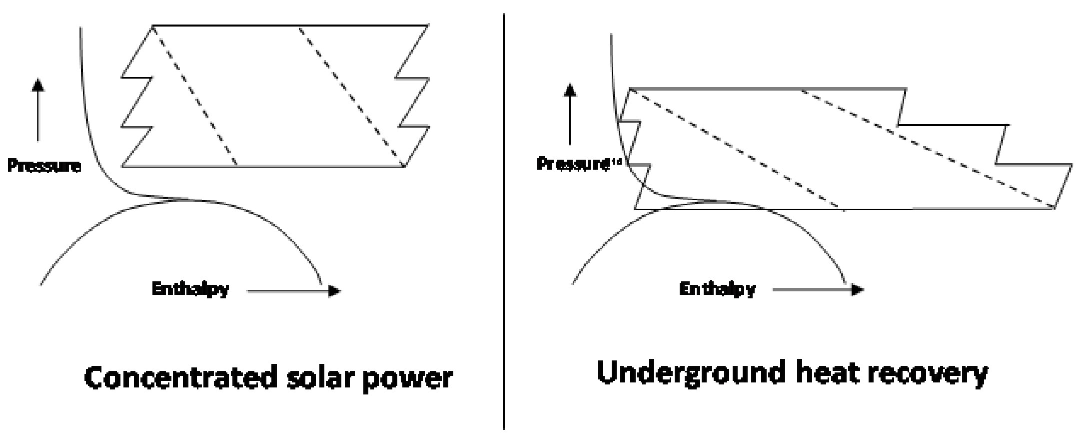


Figure 31-12: Solar heat collection with CO2

Stages	Max fluid T (deg-C):	Units	149	427
			Underground heat recovery	Concentrated solar thermal
Single	Lowest pressure	Bar		207
	Highest pressure	Bar		345
	Efficiency	%		0.532
Double	Lowest pressure	Bar	90	207
	Highest pressure	Bar	275	690
	Efficiency	%	19.1%	55.7%
Triple	Lowest pressure	Bar	70	103
	Highest pressure	Bar	275	345
	Efficiency	%	22.5%	72.6%

Table 31-3: Brayton cycle efficiencies

Another application of such water-based systems, that can have potentially huge commercial consequence, is the replacement of steam-generation electrical utilities with ones employing $scCO_2$ instead. Such plants would be smaller and cheaper. Equipment sizes – particularly turbines – would be much smaller, and operating temperatures would be low enough to permit construction with cheaper carbon steel. Carbon dioxide is non-polar and non-corrosive, so high alloy steels are not required. Ion-exchange systems for water treatment could be eliminated.

31-10 Best Practices, Environmental Regulatory Policies, and Standards

Best practices, regulations and standards play an important role in promoting and supporting energy management practices [1]. To be globally competitive companies must be able to confidently manufacture products that conform to regulatory requirements and standards, and most importantly, demonstrate this conformance when required [53]. Companies typically develop specific sets of best practices to achieve competitive advantage. They may also adopt best practices associated with a particular industry sector (aerospace, automotive) or standard (ISO 9000 Quality Management, ISO 14000 Environmental Management, ISO 50001 Energy Management). Representative examples of such practices are discussed below.

- Toyota developed superior value by partnering with suppliers to reduce its cumulative process waste. In 2000, Toyota issued its Green Supplier Guidelines where it asked the suppliers to go beyond legal and social requirements and to undertake activities that support Toyota's environmental goals. This resulted in ninety eight percent of Toyota's North American suppliers becoming ISO 14001 certified/registered. Toyota also shared its best practices and ideas with its suppliers and years later rolled out Eco-VAS, a comprehensive system used to measure and reduce the environmental impact of a vehicle across its entire life cycle. Toyota promoted energy conservation awareness throughout its supply chain, holding energy reduction events comparable to events conducted within its manufacturing plants for years [6, 54].

- For a number of years several metal casting companies, backed by industry consortiums and funded through Department of Defense and Department of Energy [55], have been developing new and innovative energy reduction best practices.
- Buildings present one of the best opportunities to economically reduce energy consumption and limit greenhouse gases [56, 57]. A number of companies are establishing procedures to measure the combined impact of manufacturing operations (e.g., plant floor resources and processes) and building services and controls (e.g., HVAC-lighting and delivery) – an important capability for accurately evaluating a company's true performance in meeting sustainability objectives.

Sustainable manufacturing is causing companies to implement new design and analysis procedures, energy reduction methods, material reduction efforts, and improved materials handling practices. A recent NIST workshop identified that current evaluation methods for energy consumption were not sufficient to measure environmental impacts [58]. Evaluation methods and decision-support tools are critical for companies to consider potential investments in energy efficiency. The evaluation methods should be able to calculate the environmental impacts, and these evaluation methods should consider the energy life cycle and source types. Additionally, there is a need for developing energy simulation models and analysis tools for a trade-off analysis between investment and environmental impacts.

31-11 Summary

In order to identify, analyze, and improve energy efficiencies, an enterprise must have a clear understanding of the performance of its production processes and the correlation of its process controlling parameters to the performance of its products. Many processes, methods, and tools currently in use for measuring energy utilization were not built upon or developed using scientific methods. Science-based approaches add credibility by establishing a foundation for the development of energy utilization processes, methods, and tools which will support measurements enabling quantifiable progress toward meeting energy use objectives. Through disciplined research and the pursuit of new resources and technologies founded on well-structured science-based methods, researchers can expect to rapidly discover and increase human knowledge and understanding of energy management and control processes. This will allow for transition and implementation of the technologies into manufacturing areas that can benefit from the structured and formalized approach that science-based approaches provide. Ultimately, engineering methodologies and tools that achieve process energy efficiency without impacting product functionality will be commonplace.

Disclaimer

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