TOTAL PLANT ENERGY EFFICIENCY

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Summary

Efficient energy use at the plant level depends on the efficient generation, conversion, management, and recovery of energy. On-site generation technologies can benefit industries, not only by increasing energy efficiency, but also by serving as a reliable, high-quality, back-up, energy source. In addition, thermal-energy storage systems can help industries manage energy supply and demand, by storing energy when it is generated for use when it is required. Heat-recovery systems are an extremely important component to total plant efficiency. Most industrial energy loss results from heat loss to the environment. The recovery of waste heat can also be combined with thermal-energy storage to maximize the usefulness of recovered heat. This article presents a brief overview of total plant efficiency, including discussions of (a) a total plant energy balance, (b) on-site generation, with particular attention to cogeneration, (c) thermal-

energy storage and its application to cogeneration, and (d) heat recovery, with emphasis on recuperators. Also presented are two case studies of cogeneration.

1. Total Plant Energy Balance

The first law of thermodynamics states that energy is neither created nor destroyed—it is conserved. Therefore, consider the energy balance of an industrial plant. The energy change within the plant is equal to the energy entering the plant minus the energy leaving the plant. If, on average, the energy within the plant does not change, but rather is converted into a useful product, the energy change within the plant has an average value of zero. In this case, the energy input to the plant equals the energy output. Figure 1 shows a simple energy balance of a generic industrial plant in which the energy flowing in equals the energy flowing out.

Figure 1. Total plant energy balance

There are three main categories of energy inputs associated with typical industrial facilities. These include:

- High-quality energy in the form of fuels, electricity, and steam
- Renewable energy, such as biomass and solar
- Raw and recycled materials

Figure 2 shows a block diagram of the energy inputs to an industrial plant. Some sort of loss characterizes each of the above energy sources. For example, to bring fossil fuels and biomass to the plant results in transportation losses. Unless the fossil fuels and biomass are present on-site, it takes energy to transport them to the facility via vehicles, natural-gas lines, or other means. (There are also losses associated with the processing of the fuels into usable forms. However, these losses are not considered in the current discussion.) Electricity and steam from utility companies incur losses in two main stages before they enter the facility. The first losses result during conversion from one type of energy (i.e., fuel, hydropower, nuclear, biomass, and solar) to another type (i.e., electricity and steam). The second stage of losses includes transmission and distribution losses of the electricity (or steam). Raw material and recycled material also have two main stages in which they incur energy losses. Losses in the first stage occur in conversion from the raw or recycled state to a usable state, and losses in the second stage result during transportation to the facility. The only category of energy input that is considered to have no losses in transit to the on-site facility is renewable energy that is already present on-site. This could include solar, wind, biomass, and/or waste off-gas energy.

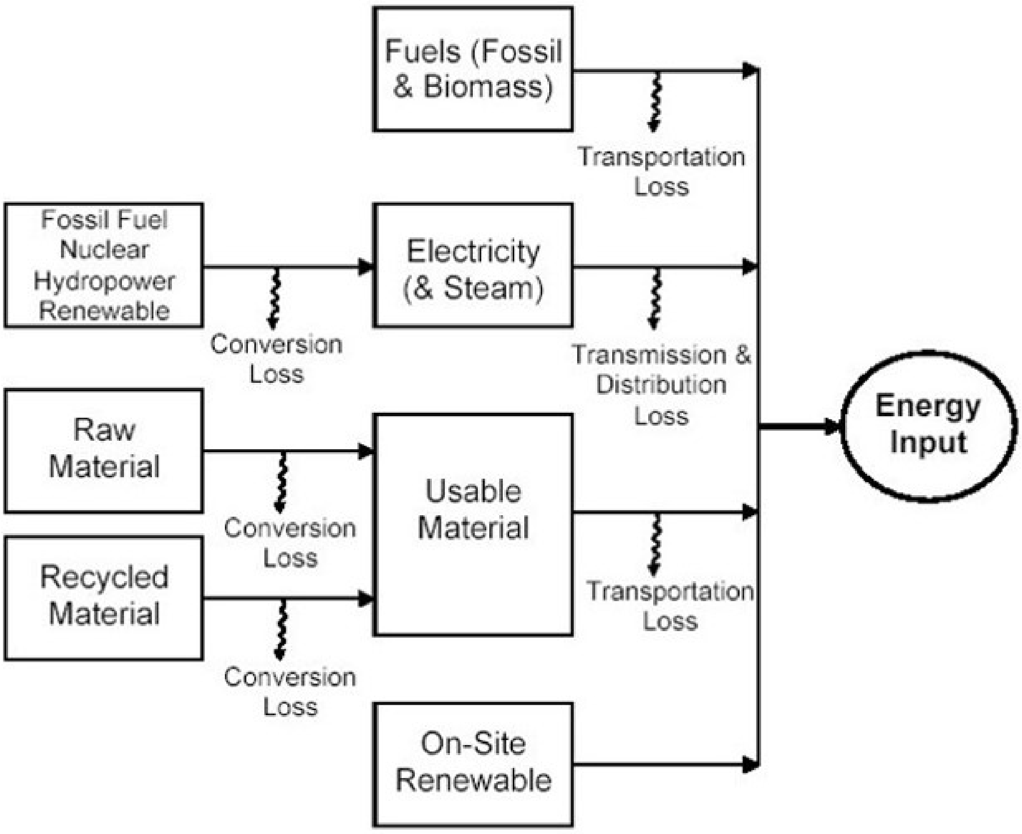

Figure 2. Energy inputs to an industrial plant

It is somewhat beyond the control of the industrial plant to minimize conversion, transportation, distribution, and transmission losses. The losses have already occurred by the time the energy is on-site. However, industries do have the option of on-site generation. By utilizing on-site generation technologies with heat recovery, many energy losses are avoided. In addition, power quality and reliability are often increased. The downside is that the costs may be very high, and more pollution is generated on-site, rather than away from the facility at the power plant. Due to stringent air quality standards, and limits on emissions for individual facilities, the additional emissions from on-site generation may lead to air quality violations.

Figure 3 shows the energy outputs of a typical industrial plant. The most desired output of the plant is its product. The product should be of the highest quality with the smallest expenditure of energy or cost. The energy intensity of a product is a measure of the quantity of energy required to obtain the product. Two other desirable energy outputs from a plant are extra energy and surplus materials that can be sold for a profit. For example, if more electricity is produced on-site than is necessary for the process, the excess can be sold to a utility or other facility. In addition, scrap materials can be salvaged and sold for a profit.

The two undesirable energy losses include waste heat and waste materials. To maximize total plant energy efficiency, the quantities of waste heat and waste materials need to be minimized. This is accomplished by utilizing effective heat recovery techniques on-site.

The goal is to reduce the quality (usable energy content) of the waste heat as much possible before the heat is lost to the environment. In the process of recovering heat, the energy should be used to its full potential by the concept of cascading. The idea of cascading is to use the higher quality energy for applications that require a more organized energy source, and then use lower quality energy for applications with lower requirements, and so on down the cascade. Applications at the bottom of the cascade should include systems with very low quality energy demands, such as space heat. In other words, it is very inefficient to take waste heat at 540 °C (1000 °F), cool it, and use it for heating office space. It is also wise to recover and recycle scrap materials. Materials have a significant energy content associated with them. The energy required to obtain usable materials from recycled materials is considerably less than it is from raw materials. In some cases, it is cost prohibitive to realize the maximum potential of energy from waste heat and waste materials; however, as fuel prices continue to rise, there will be an increasing incentive for efficient energy recovery.

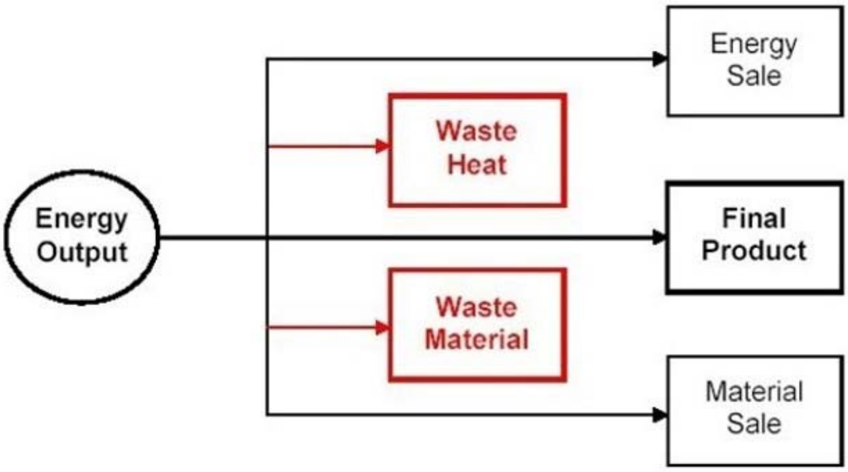

Figure 3. Energy outputs of an industrial plant

Figure 4 shows the main elements that contribute to energy use and conversion within a typical industrial plant. As mentioned earlier, energy is not created; it is just converted from one form to another. Therefore, consider the elements that are used to convert the energy that is input to a system (in this case, the system being an industrial plant). These elements include the on-site generation equipment, the operation of the facility or individual buildings, the process equipment and materials, and the air pollution control systems.

If available and utilized at a given site, the on-site generation equipment is capable of converting fuel into electricity, steam, and hot water. To operate the buildings and facilities within the plant, energy inputs (electricity, fuels, waste heat, and/or renewables) are converted into lighting, HVAC, hot water, etc. For operation of the process equipment, energy inputs are converted to mechanical energy, steam, process heat, etc. In addition, the energy from the process systems, combined with the energy content of the input materials, contributes to the increase in energy content of the final products. Finally, the air-pollution control systems use energy inputs to remove particulates and gaseous contaminants from the exhaust gases. In many cases, waste heat is generated during conversion from one form of energy to another. The percentage of waste heat that is recovered is a major determining factor of the total plant efficiency. In addition, thermal-energy storage is a technique that can be used to take advantage of heat at a later time. This can result in load reductions during peak demand periods. Another way to improve efficiency is to recover and reuse waste materials. It may also be possible to sell excess energy and materials for a profit.

The goal for maximum total energy efficiency is to limit wasted energy and wasted materials through effective conversion and energy cascading. At the same time, product quality and air quality should not be compromised. Sections 2–4 discuss specific techniques to improve total plant efficiency, including on-site generation, thermal-energy storage, and heat recovery.

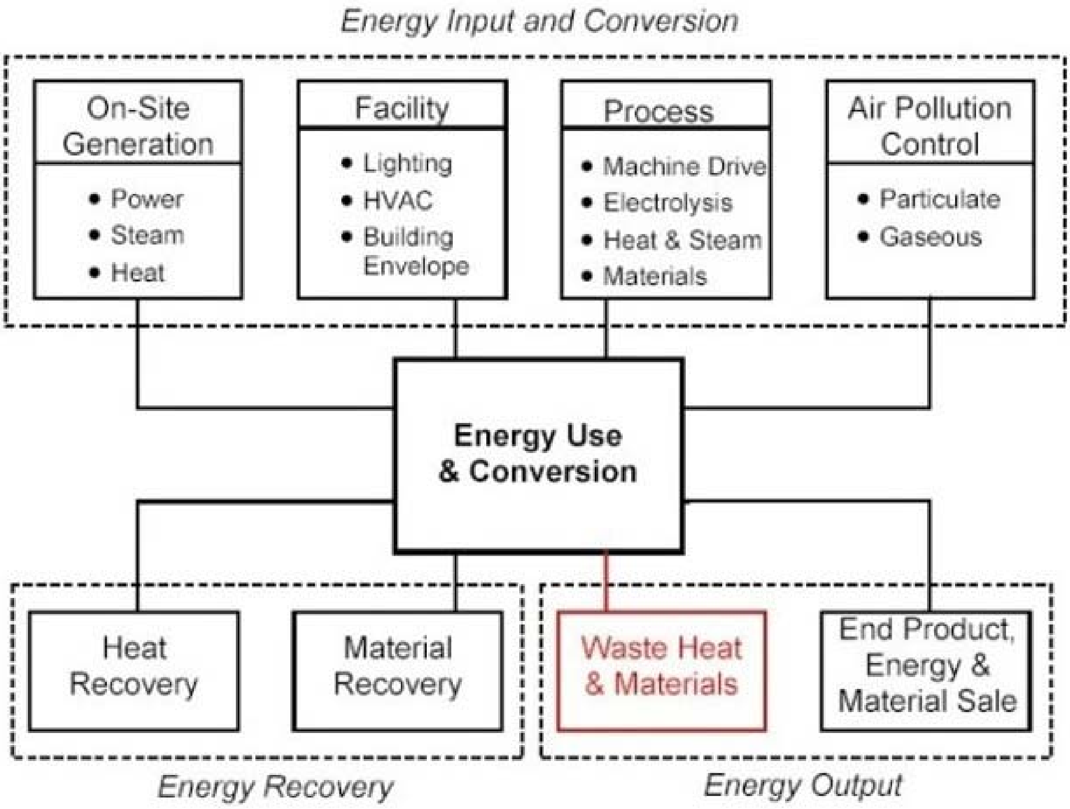

Figure 4. Energy use and conversion within an industrial plant

2. On-Site Generation

2.1. Overview

On-site generation systems are used to produce electricity, mechanical energy, steam, and/or hot water at the point of usage. They are also installed to provide supplemental or back-up power, and for load management. There are a variety of generation technologies, such as internal combustion engines, gas turbines, fuel cells, batteries, advanced gas turbines, gas engines, and solar photovoltaics. Some applications require only electricity generation on-site; others have a need for electricity and thermal energy.

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Technologies that are capable of electric and thermal-energy generation are termed cogeneration systems. Some of the primary benefits of on-site generation are listed here.

- Increased energy efficiency. On-site generation systems are very efficient since they have relatively small energy losses associated with them. For example, the transmission and distribution losses that characterize electricity from power plants are avoided by having systems on-site. The efficiency is particularly high for technologies with heat recovery.
- Supplemental power. On-site generation systems can supplement the power that is provided by off-site utilities. This is advantageous for industries that want to increase capacity, but do not have the support of additional power from local utilities. For example, the utilities may be operating at full capacity, and therefore unable to meet the additional demand.
- Back-up generation. On-site systems can provide reliable standby generation capacity. They are useful during emergencies and scheduled power outages.
- Fuel diversification. Some on-site systems are capable of burning landfill gas, digester gas, coal-steam methane gas, and industrial off-gas. This works to the benefit of industries that have alternate fuels at their disposal.
- Power quality and reliability. In many cases power quality and reliability are increased with on-site generation systems.
- Cogeneration. For industries requiring electricity and thermal energy, cogeneration systems provide a very energy-efficient alternative to purchasing electricity and fuel.
- Electricity sales. On-site generation systems can also result in a profit from electricity sales for industries with a surplus of power generation. Utilities and other customers can purchase the unneeded electricity, providing additional income to the industrial plant.
- Utility support. Utilities benefit from industrial on-site generation in the event that they are unable to meet current demand, or during peak demand periods. Increased on-site generation capacity can also help to delay the need for additional power plants.

In addition to benefits, there are also several barriers to the increased application of on-site generation. Some of the barriers include

- High capital requirement. On-site generation systems can sometimes have very high initial costs, with relatively low return-on-investment values. Even though energy efficiency is typically increased with on-site systems, utility companies are often able to provide the required energy in a more cost-effective manner. However, as the price of fuel increases, and the price of on-site generation technologies decrease, there will be more of an economic incentive for on-site generation. Section 2.3 presents a case study that is an example of this type of barrier. It describes a study in which the application of a cogeneration system yielded a benefit-to-cost ratio of less than one.
- Increased space. On-site systems require additional space for the generation equipment and for air pollution control equipment.

- Increased employment of skilled personnel. Having more equipment generally requires more maintenance personnel. The personnel need to have the appropriate skills for equipment operation.
- Increased on-site emissions. In many cases, the on-site generation equipment will have emissions that need to be controlled. This will require air pollution control equipment. It is also possible that emissions will exceed regulated values.

Some of the incentives to overcome the barriers to on-site generation include (a) its potential for lower electricity costs in light of increasing off-site utility costs, (b) monetary incentives for the application of energy-efficient technologies, and (c) relaxed regulations for users of energy-efficient technologies. In addition, on-site generation may prove indispensable in the event of utility power shortages.

Section 2.2 discusses on-site cogeneration in greater detail. Various cogeneration technologies and applications are presented, along with future trends. Section 2.3 presents two case studies of cogeneration. The first illustrates the benefit of cogeneration during power shortages and the second illustrates one of the barriers to cogeneration's widespread application.

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Biographical Sketches

Clark Gellings’ 30-year career in energy spans from hands-on wiring in factories and homes to the design of lighting and energy systems to his invention of “demand-side management” (DSM). Mr. Gellings coined the term DSM and developed the accompanying DSM framework, guidebooks, and models now in use throughout the world. He provides leadership in EPRI, an organization that is second in the world only to the Department of Energy (in dollars) in the development of energy-efficiency technologies. Mr. Gellings has demonstrated a unique ability to understand what energy customers want and need and then implement systems to develop and deliver a set of research and development programs to meet the challenge. Among Mr. Gellings’ most significant accomplishments is his success in leading a team with an outstanding track record in forging tailored collaborations—alliances among utilities, industry associations, government agencies, and academia—to leverage research and development dollars for the maximum benefit. Mr. Gellings has published 10 books, more than 400 articles, and has presented papers at numerous conferences. Some of his many honors include seven awards in lighting design and the Bernard Price Memorial Lecture Award of the South African Institute of Electrical Engineers. He has been elected a fellow in the Institute of Electrical and Electronics Engineers and the Illuminating Engineering Society of North America. He won the 1992 DSM Achiever of the Year Award of the Association of Energy Engineers for having invented DSM. He has served as an advisor to the U.S. Congress Office of Technical Assessment panel on energy efficiency, and currently serves as a member of the Board of Directors for the California Institute for Energy Efficiency.

Kelly E. Parmenter, PhD is a mechanical engineer with expertise in thermodynamics, heat transfer, fluid mechanics, and advanced materials. She has 14 years of experience in the energy sector as an engineering consultant. During that time, she has conducted energy audits and developed energy management programs for industrial, commercial, and educational facilities in the United States and in England. Recently, Dr. Parmenter has evaluated several new technologies for industrial applications, including methods to control microbial contamination in metalworking fluids, and air pollution control technologies. She also has 12 years of experience in the academic sector conducting experimental research projects in a variety of areas, such as mechanical and thermal properties of novel insulation and ablative materials, thermal contact resistance of pressed metal contacts, and drag reducing effects of dilute polymer solutions in pipeflow. Dr. Parmenter’s areas of expertise include: energy efficiency, project management, research and analysis, heat transfer, and mechanical and thermal properties of materials.

Patricia Hurtado, P.E. is a mechanical engineer with a master's degree in thermal sciences and over 20 years experience in the energy sector. She has worked as an energy planner for more than 10 years, conducting projects related to energy conservation, pollution reduction, building analysis, engineering modeling, strategic planning, market evaluation, program development and performance assessment, distribution and retail sector analysis, privatization evaluation in the electric utility sector, as well as energy sector restructuring, rate design and analysis. Her consulting assignments have included clients in the United States, Puerto Rico, Mexico, Colombia, and Thailand. Ms. Hurtado’s areas of expertise include: energy system design and analysis, engineering simulation models, end-use data and engineering analysis, economic analysis, utility resource and strategic planning, forecasting, rate design and analysis, distribution and retail sector analysis, and technology and market assessments of new products and services.