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MANUFACTURING

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Industrial production is the backbone for economic output in almost all countries. Over the past decades, manufacturing industrial production has been growing in most economies. The industrial sector is dominated by the production of a few major energy-intensive commodities such as steel, paper, cement, and chemicals. In any given country or region, production of these basic commodities follows the general development of the overall economy. Rapidly industrializing countries will have higher demands for infrastructure materials and more mature markets will have declining or stable consumption levels. The regional differences in consumption patterns (expressed as consumption per capita) will fuel a further growth of consumption in developing countries. In these 'heavy' industries energy is a very important production cost factor, besides labor costs and costs for raw materials, driving a change towards higher energy efficiency (see Table 1). Markets in the industrialized countries show a shift towards more service oriented activities, and hence non-energy intensive industries. Because of the great difference in energy intensity between energy intensive industries and all others, changes in output shares of these industries can have a major impact on total industrial energy use. Many commodities, e.g., food, steel, are traded globally and regional differences in supply and demand will influence total industrial energy use. Production trends also depend on regional availability of resources (e.g. scrap) and capital. Manufacturing energy use will also depend on the energy efficiency with which the economic activities are done. In this article we will assess trends in industrial energy use and energy intensities, followed by a discussion of energy services, uses and industrial technologies.

Global Manufacturing Energy Use

In 1990, manufacturing industry accounted for 42% (129 EJ) of global energy use. Between 1971 and 1990, industrial energy use grew at a rate of 2.1% per year, slightly less than the world total energy demand growth of 2.5% per year. This growth rate has slowed in recent years, and was virtually flat between 1990 and 1995, primarily because of declines in industrial output in the transitional economies in Eastern Europe and the former Soviet Union. Energy use in the industrial sector is dominated by the industrialized countries, which accounted for 42% of world industrial energy use in 1990. Industrial energy consumption in these countries increased at an average rate of 0.6% per year between 1971 and 1990, from 49 EJ to 54 EJ (Exajoule (EJ) = 10^{18}J) (Price et al, 1998). The share of industrial sector energy consumption within the industrialized countries declined from 40% in 1971 to 33% in 1995. This decline partly reflects the transition toward a less energy-intensive manufacturing base, as well as the continued growth in transportation demand, resulting in large part from the rising importance of personal mobility in passenger transport use.

The industrial sector dominates in the economies in transition, accounting for more than 50% of total primary energy demand, the result of the emphasis on materials production, a long term policy promoted under years of central planning. Average annual growth in industrial energy use in this region was 2.0% between 1971 and 1990 (from 26 EJ to 38 EJ), but dropped by an average of –7.3% per year between 1990 and 1995.

In the Asian developing countries, between 1971 and 1995 industrial energy use grew rapidly between 1971 and 1995, with an annual average growth rate of 5.9%, jumping from 9 EJ to 35 EJ (Price et al.,1998). It also accounted for the greatest share of primary energy consumption , between 57% and 60%. The fastest growth in this sector was seen in China and in other rapidly-developing Asian countries. Growth in other developing countries was slightly lower.

The nature and evolution of the industrial sector varies considerably among developing countries. Some economies that are experiencing continued expansion in energy-intensive industry, such as China and India, show relatively unchanging shares of industrial energy use. In other countries, such as Thailand and Mexico, the share and/or growth of the transportation sector dominate. Many smaller countries have remained primarily agrarian societies with modest manufacturing infrastructure.

Energy Intensity Trends

In aggregate terms, studies have shown that technical efficiency improvement of 1 to 2% per year has been observed in the industrial sector in the past (Ross and Steinmeyer, 1990). During and after the years of the oil shock U.S. industrial energy intensity declined by 3.5%/year (between 1975 and 1983). Between 1984 and 1994 industrial energy intensity declined by less than 1% on average (Brown et al., 1998). Figure 1 gives an overview of energy intensity trends in the industrial sector in industrialized countries.

The trends demonstrate the capability of industry to improve energy efficiency, when it has the incentive to do so (Brown et al., 1998). Energy requirements can be cut by new process development. In addition, the amount of raw materials demanded by a society tends to decline as countries reach certain stages of industrial development, which leads to a decrease in industrial energy use. The accounting of trends in structural shift, material intensity and technical energy efficiency and their interactions can be extremely difficult. To understand trends in energy intensity it is important to analyze the structure of the industrial sector. Industrial energy use can be broken down into that of the energy-intensive industries (e.g. primary metals, pulp and paper, primary chemicals, oil refining, building materials) and the non-energy intensive industries (e.g. electronics and food). Reduction of energy intensity is closely linked to the definition of structure, structural change, and efficiency improvement. Decomposition analysis is used to distinguish the effects of structural change and efficiency improvement. Structural change can be broken down into intra-sectoral (e.g. a shift towards more recycled steel), inter-sectoral (e.g. a shift from steel to aluminum within the basic metals industry). A wide body of literature describes decomposition analyses (see e.g. Schipper and Meyers, 1992; Howarth et al., 1991; Ang, 1995), and explains the trends in energy intensities and efficiency improvement. Decomposition analyses of the aggregate manufacturing sector exist mainly for industrialized countries (IEA, 1997d), but also for China (Sinton and Levine, 1994), Taiwan (Ang and Pandiyan, 1997; Li et al., 1990) and selected countries including Eastern Europe (Park et al., 1993). The results show that different patterns exist for various countries, which may be due to specific conditions as well as differences in driving forces such as energy prices and other policies in these countries (IEA, 1997d). More detailed analyses on the sub-sector level are needed to understand these trends better. Changes in energy intensities can also be disaggregated into structural changes and efficiency improvements at the sub-sector level. In the iron and steel industry, energy intensity is influenced by the raw materials used (i.e. iron ore, scrap) and the products produced (e.g. slabs, or thin rolled sheets). A recent study on the iron and steel industry used physical indicators for production to study trends in seven countries which together produced almost half of the world’s steel (Worrell et al., 1997b). Figure 2 shows the trends in physical energy intensity in these countries, expressed as primary energy used per tonne of crude steel. The large differences in intensity among the countries are shown, as well as the trends towards reduced intensity in most countries. Actual rates of energy efficiency improvement varied between 0.0% and 1.8% per year, while in the case of the restructuring economy of Poland the energy intensity increased.

Energy Services and Energy Efficiency

Energy is used to provide a service, e.g. a ton of steel, or to light a specified area. These services are called energy services. Energy efficiency improvement entails the provision of these services using less energy. About half of industrial energy use is for specific processes in the energy intensive industries. On the other hand, various general energy conversion technologies and end-uses can also be distinguished, e.g. steam production, motive power, and lighting. Hence, energy use in manufacturing industry can be broken down in various uses to provide a variety of services. A common breakdown distinguishes energy use for buildings, processes and utilities and boilers. The boilers provide steam and hot water to the processes and the buildings. Due to the wide variety in industrial processes, we will limit the discussion to two energy intensive sectors, i.e. iron and steel, and pulp and paper industries, as well as boilers, as an example of an important cross-cutting energy consuming process in industry.

Iron and Steel Industry.

The first record of the use of iron goes back to 2500-2000 BC, and the first deliberate production of iron began around 1300 BC. Small furnaces using charcoal were used. Evidence of such furnaces has been found in Africa, Asia and central Europe. The cold temperatures in the furnace lead to low quality iron, and the slag had to be removed by hammering the iron. High temperature processes started to be introduced in Germany around 1300 AD. The design of these furnaces is essentially the same of that of modern blast furnaces. The furnaces still used charcoal, and in 1718 the first use of coke is reported in the United Kingdom. The higher strength of coke allowed larger furnaces to be build, increasing energy efficiency. By 1790 coke iron making contributed to 90% of the British iron production (De Beer et al., 1998a). Between 1760 and 1800 energy use declined by about 2%/year, mainly through the use of steam engines permitting higher blast pressures. During the 19th century coke demand was further reduced by 1% per year. The development of the modern blast furnace after the second world war, resulted in an annual reduction of energy intensity of 3-4%/year, due to the use of improved raw materials, ore agglomeration, larger blast furnaces and higher air temperatures (De Beer et al, 1998a). Today the blast furnace is the main process to make iron, and provides the largest raw material stream in steelmaking.

Steel is made by reducing the carbon content in the iron to levels below 2%. This reduces the brittleness of the material, and makes it easier to shape. The first steelmaking process was invented in 1855 by Bessemer, and went into commercial operation by 1860. In the Bessemer convertor air was blown through the hot iron, which oxidizes the carbon. This principle is still followed in modern steelmaking processes. In the U.S. the last Bessemer convertor was retired in the 1960's. In the late 19th century the open hearth or Siemens-Martin furnace (OHF) was invented, which uses preheated air and fuels to oxidize the carbon, and melt the steel. This process is currently only found in developing countries and in Eastern Europe. The U.S. was one of the industrialized countries that phased out OHF at a very late stage. In the 1980's the dominant process became the basic oxygen furnace (BOF), using pure oxygen instead of air. The BOF process was developed in Austria in the 1950's. The productivity of this process is much higher, as is the energy efficiency. An alternative process is the electric arc furnace (EAF). The EAF process is mainly used to melt scrap. Performance of EAFs has improved tremendously, starting to use fuel and oxygen besides electricity. In the future it is expected that the BOF and EAF process will follow similar development paths.

Liquid steel is cast into ingot or slabs, and shaped in rolling mills to the final product. Although most energy use is concentrated in the iron and steelmaking, reduced material losses and productivity gains in casting and shaping (e.g. continuous casting, and currently thin slab casting) have contributed to dramatic increases in the energy efficiency of steelmaking.

Today, the U.S. iron and steel industry is made up of *integrated steel mills* that produce pig iron from raw materials (iron ore, coke) using a blast furnace and steel using a basic oxygen furnace (BOF) and *secondary steel mills* that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). The majority of steel produced in the U.S. is from integrated steel mills, although the share of secondary steel mills (or “minimills”) is increasing, growing from 15% of production in 1970 to 40% in 1995. There were 142 operating steel plants in the U.S. in 1997, of which 20 are integrated steel and 122 minimills. The integrated mills are most often located near or with easy access to the primary resources, e.g. in the U.S. these are concentrated in the Great Lakes region, near supplies of coal and iron ore and near key customers such as the automobile manufacturers.

The worldwide average energy intensity of steelmaking is estimated at 24 GJ/tonne, although large variations occur between countries and plants (see Figure 2). Today the most energy efficient process would use 19 GJ/tonne for integrated steelmaking, and 7 GJ/tonne for making steel out of scrap. Analyses have shown that many technologies exist that could improve energy efficiency further. For example in the U.S. the potential for energy efficiency improvement is estimated at 18%, using proven and cost-effective practices and technologies (Worrell et al., 1999). New technologies are under development, which could considerably lower the energy intensity of steelmaking. Smelt reduction in ironmaking would integrate the production of coke and agglomerated ore with that of iron making, leading to reductions in production costs and energy use. The development of direct casting techniques, that abandon rolling, would increase productivity while reducing energy use further. Combined, these technologies could reduce the energy intensity of primary steelmaking to 12.5 GJ/tonne steel, and for secondary steelmaking to 3.5 GJ/tonne, a reduction of 34% and 50% relatively (De Beer et al, 1998a). In the highly competitive and globalizing steel industry, manufacturers must continuously look for ways to lower their energy intensity and costs.

Pulp and Paper Industry.

Paper consists of aligned cellulosic fibers. The fibers may be from wood or other crops, or from recycling waste paper. Starting with wood fibers, the fibers need to be separated from the wood, which is done by pulping the wood. The separation can be done by chemicals, heat or by mechanical means. In the chemical pulping process chemicals and hot water are used to separate the cellulosis from the ligno-cellulosis. The amount of pulp produced is about half of the amount of wood used. Chemical pulping results in high quality paper. In mechanical the wood is ground under pressure, separating the fibers from each other. In mechanical pulping the ligno-cellulosis is generally not removed, resulting in a lower quality paper, e.g. used for newsprint, but also a higher recovery (about 90% of the used wood). In chemical pulping a lot of steam is used to heat the water and concentrate the chemical by-products. However, recovery of the by-products to be recycled in the process can actually produce sufficient steam for the whole paper mill. The mechanical process uses large quantities of electricity, while some processes can recover steam from the grinding process. Chemical pulp can be bleached to produce white paper. Waste paper is being pulped by mixing with water, after which ink is removed and the pulp refined. Paper recycling reduces the energy needs for the pulping process. Waste paper use in the production of paper varies widely, due to the different structures of the industry in different countries (Farla et al., 1997).

While energy efficiency improvement options do exist in the pulping step, greater opportunities exist in the chemical recovery step. The most common pulping process in the U.S. is the Kraft pulping process. Black liquor is produced as a by-product. The chemicals are currently recovered in a recovery boiler, combusting the ligno-cellulosis. Because of the high water content, the efficiency of the recovery boiler is not very high, and the steam is used to generate electricity in a steam turbine and steam for the processes. Gasification of black liquor would allow the use of the generated gas at a higher efficiency. This would make a Kraft pulp mill an electricity exporter (Nilsson et al, 1995).

In papermaking the pulp is diluted with water at about 1:100. This pulp is screened and refined. The solution with the refined fibers (or stock) is fed to the papermachine, where the water is removed. In the paper machine, the paper is formed into a sheet, and water removed by dispersing over a wire screen. At the end of the forming section, 80% of the water is removed. The rest of the water is removed in the pressing and drying section. While only a small amount of water is removed in the drying section, most energy is used in the drying section. Hence, energy efficiency opportunities try to reduce the water content by increasing the water removal by pressing. In a long nip press, the pressing area is enlarged. The larger pressing area results in extra water removal. New technologies are under development aiming to increase the drying efficiency considerably. One technology, impulse drying, uses a heated roll, pressing out most of the water in the sheet that may reduce the steam consumption of the papermachine by 60-80% (De Beer et al., 1998b).

The pulp and paper industry uses approximately 6-8 EJ globally (WEC, 1995; Farla et al., 1997). Because energy consumption and intensity depends on the amount of wood pulped, the type of pulp produced, as well as the paper grades produced, there is a great range in energy intensities among industrialized countries of the world. In Europe energy use for papermaking varied between 16 GJ/tonne to 30 GJ/tonne of paper in 1989 (Worrell et al., 1994). The Netherlands used the least energy per tonne of paper, largely because most of the pulp was imported. Countries like Sweden and the U.S. have much higher energy intensities due to the larger amount of pulp produced. Sweden and other net exporters of pulp, also tend to show a higher energy intensity. Energy intensity is also influenced by the efficiency of the processes used. Many studies have shown considerable potentials for energy efficiency improvement with current technologies (Worrell et al., 1994; Nilsson et al., 1995; Farla et al., 1997), such as heat recovery, and improved pressing technologies.

Cross-Cutting – Steam Production and Use.

Besides the energy intensive industries, many smaller and less energy intensive, or light, industries exist. Light industries can include food processing, metal engineering, or electronics industries. In light industries energy is generally a small portion of the total production costs. There is a wide variety of processes used within these industries. Generally a large fraction of energy is used in space heating and cooling, motors (e.g. fans, compressed air) and in boilers. Industrial boilers are used to produce steam or heat water for space and process heating and for the generation of mechanical power and electricity. In some cases, these boilers will have a dual function, such as the cogeneration of steam and electricity. The largest uses of industrial boilers by capacity are in paper, chemical, food production and petroleum industry processes. Steam generated in the boiler may be used throughout a plant or site. Total installed boiler capacity (not for cogeneration) in the U.S. is estimated at nearly 880 million MW. Total energy consumption for boilers in the U.S. is estimated at 9.9 EJ.

A systems approach may substantially reduce the steam needs, reduce emissions of air pollutants and greenhouse gases, as well as reduce operating costs of the facility. A systems approach assessing options throughout the steam system that incorporates a variety of measures and technologies is needed (Zeitz,1997) can help to find low cost options. Improved efficiency of steam use reduces steam needs, and may reduce the capital lay-out for expansion, reducing emissions and permitting procedures at the same time. Table 2 summarizes various options, to reduce losses in the steam distribution, improve system operation and the boiler itself. In specific cases, the steam boiler can be replaced almost totally by a heat pump (or mechanical vapor recompression) to generate low-pressure steam. This replaces the fuel use for steam generation by electricity. Emission reductions will depend on the type and efficiency of power generation.

Another option to reduce energy use for the steam system is cogeneration of heat and power (CHP) based on gasturbine technology is a way to substantially reduce the primary energy needs for steam making. Low and medium pressure steam can be generated in a waste heat boiler using the fluegases of a gasturbine. Classic cogeneration systems are based on the use of a steam boiler and a back-pressure turbine. These systems have a relatively low efficiency compared to a gasturbine system. Steam-turbine systems have generally a power-to-heat ratio between 0.15 (40 kWh/GJ) and 0.23 (60 kWh/GJ) (Nilsson et al., 1995). The power-to-heat ratio depends on the specific energy balance of plant, as well energy costs. A cogeneration plant is most often optimized to the steam load of the plant, exporting excess electricity to the grid. The costs of installing a steam turbine system strongly depend on the capacity of the installation. Gas turbine based cogeneration plants are relatively cheap. In many countries, e.g. The Netherlands, Scandinavia, gas turbine cogeneration systems are standard in paper mills. The power-to-heat ratio is generally higher than for steam turbine systems. Aero-derivative gas turbines may have a power-to-heat ratio of 70-80 kWh/GJ (Caddet,1999). Aeroderivative turbines are available at low capacities, but specific costs of gas turbines sharply decrease with larger capacities.

Potential for Energy Efficiency Improvement

Much of the potential for improvement in technical energy efficiencies in industrial processes depends on how closely such processes have approached their thermodynamic limit. There are two types of energy efficiency measures: (1) more efficient use in existing equipment through improved operation, maintenance or retrofit of equipment; and 2) use of more efficient new equipment, by introducing more efficient processes and systems at the point of capital turnover or expansion of production. More efficient practices and (new) technologies exist for all industrial sectors. Table 2 outlines some examples of energy efficiency improvement techniques and practices.

A large number of energy-efficient technologies are available (see Table 3 and above) in the steel industry including continuous casting, energy recovery and increased recycling. Large technical potentials exist in most countries, ranging from 25 to 50%, even for industrialized countries (WEC,1995). New technologies are under development, e.g. smelt reduction and near net shape casting, that will reduce energy consumption, as well as environmental pollution and capital costs. A few bulk chemicals, e.g. ammonia, ethylene, represent the bulk of energy use in this sub-sector. Potentials for energy savings in ammonia making are estimated to be up to 35% in Europe and of between 20% and 30% in Southeast Asia (WEC,1995). Energy savings in petroleum refining are possible through improved process integration, cogeneration, energy recovery and improved catalysts. Compared to state-of-the-art technology, the savings in industrialized countries are estimated to be 15-20%, and higher for developing countries (WEC,1995). Large potentials for energy savings exist in nearly all process stages of pulp and paper production, e.g. improved dewatering technologies, energy and waste heat recovery and new pulping technologies. Technical potentials are estimated up to 40%, with higher long term potentials (see above). Energy savings in cement production are possible through increased use of additives (replacing the energy-intensive clinker), use of dry process and a large number of energy efficiency measures (e.g. reducing heat losses and use of waste as fuel). Energy savings potentials of up to 50% do exist in the cement industry in many countries through efficiency improvement and the use of wastes like blast furnace slags and fly-ash in cement making.

In the United States various studies have assessed the potential for energy efficiency improvement in industry. One study has assessed the technologies for various sectors, and found potential economic energy savings of 7 to 13% over the business as usual trends (Brown et al., 1998) between 1990 and 2010. Technologies like the ones described above (see Table 2) are important in achieving these potentials.

However, barriers may partially block the uptake of those technologies. Barriers to efficiency improvement can include: unwillingness to invest, lack of available and accessible information, economic disincentives, and organizational barriers (Worrell et al., 1997a). The degree in which a barrier limits efficiency improvement is strongly dependent on the situation of the actor (e.g. small companies, large industries). A range of policy instruments is available, and innovative approaches or combinations have been tried in some countries. Successful policy can contain regulation (e.g. product standards) and guidelines, economic instruments and incentives, voluntary agreements and actions, information, education and training, and research, development and demonstration policies. Successful polices with proven track records in several sectors include technology development, and utility/government programs and partnerships. Improved international cooperation to develop policy instruments and technologies to meet developing country needs will be necessary, especially in light of the large anticipated growth of the manufacturing industry in this region.

Summary

Manufacturing industry is a large energy user in almost all countries. About half of industrial energy use is used in specific processes in the energy intensive industries. On the other hand, various general energy conversion technologies and end-uses can also be distinguished, e.g. steam production, motive power, and lighting. Opportunities and potentials exist for energy savings through energy efficiency improvement in all sectors and countries. Technology development, and policies aimed at dissemination and implementation of these technologies can help to realise the potential benefits. Technologies do not now, nor will in the foreseeable future, provide a limitation on continuing energy efficiency improvements.

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Figure 1. Industrial Sector Economic Energy Intensity Trends in Selected Industrialized Countries, 1970-1995. Source: Lawrence Berkeley National Laboratory, Berkeley, CA.

Figure 2. Trends in Physical Energy Intensity (GJ/tonne crude steel) in Seven Countries Between 1971 and 1994. Source: Worrell et al., 1997b.

Table 1. Energy intensities and energy costs in selected U.S. industries. Energy intensity is expressed in primary energy, where the efficiency of electricity generation is assumed to be 33%. Energy intensity of primary aluminum production is given in MWh (1000 kWh).

Sector	**1973**		**1985**		**1994**	
	Energy Intensity (primary energy)	Energy Costs (share of production costs)	Energy Intensity (primary energy)	Energy Costs (share of production costs)	Energy Intensity (primary energy)	Energy Costs (share of production costs)
Iron & Steel	30.5 GJ/t	7%	27.8 GJ/t	11%	25.4 GJ/t	8%
Pulp & Paper	43.1 GJ/t	6%	42.7 GJ/t	6%	32.8 GJ/t	6%
Cement	7.3 GJ/t	40%	5.2 GJ/t	36%	5.4 GJ/t	33%
Primary Aluminum	N/A	14%	17.6 MWh/t	19%	16.2 MWh/t	13%
Petroleum Refining	6.2 GJ/t	4%	4.3 GJ/t	3%	4.5 GJ/t	3%

Source: Lawrence Berkeley National Laboratory, Berkeley, CA.

Table 2. Energy Efficiency Measures and estimated improvement potentials for steam boilers.

Energy Efficiency Measure	**Typical Energy Savings (%)**	**Payback Estimate (years)**
Distribution System		
Reducing Steam Leaks	3-5%	
Insulating Steam Pipes	5-10%	0.3- 1.7 year
Condensate Return	10-20%	< 1 year
Process Integration & Heat Recovery	5-40%	2-
System Operation and Maintenance		
Water Treatment	10-12%	
Load Control	3-5%	
Decentralization Steam Supply	< 40%	< 4 years
Hot Standby		
Boilers		
Boiler Tune-Up	1-2%	
Combustion Air Preheating	< 12%	< 5 years
Boiler Feed Preheating	2-10%	< 4 years
New Low-NOx Boiler Type	>5%	n.a.
Monitoring and Control	1-4%	< 3 years

Source: Prindle et al., 1995, Jones, 1997, Caddet, 1999.

Table 3. Examples of efficiency improvement measures in energy intensive industry.

Iron and Steel
Heat recovery for steam generation, pre-heating combustion air, and high efficiency burners
Adjustable speed drives, heat recovery coke oven gases, and dry coke quenching
Efficient hot blast stove operation, waste heat recovery for hot blast stove, top gas power recovery turbines, direct coal injection
Recovery BOF-gas, heat recovery of sensible heat BOF-gas, closed BOF-gas-system, optimized oxygen production, increase scrap use, efficient tundish preheating
UHP-process, Oxy-fuel injection for EAF plants, and scrap preheating
Heat recovery (steam generation), recovery of inert gases, efficient ladle preheating
Use of continuous casting, 'Hot connection' or direct rolling, recuperative burners
Heat recovery, efficient burners annealing and pickling line, continuous annealing operation

Chemicals
Process management and thermal integration (e.g. optimization of steam networks, heat cascading, low and high temperature heat recovery, heat transformers), mechanical vapor recompression
New compressor types
New catalysts
Adjustable speed drives
Selective steam cracking, membranes
High temperature cogeneration and heat pumps
Autothermal reforming

Petroleum Refining
Reflux overhead vapor recompression, staged crude pre-heat, mechanical vacuum pumps
Fluid coking to gasification, turbine power recovery train at the FCC, hydraulic turbine power recovery, membrane hydrogen purification, unit to hydrocracker recycle loop
Improved catalysts (reforming), and hydraulic turbine power recovery
Process management and integration

Pulp and Paper
Continuous digester, displacement heating/batch digesters, chemi-mechanical pulping
Black liquor gasification/gasturbine cogeneration
Oxygen predelignification, oxygen bleaching, displacement bleaching
Tampella recovery system, falling film black liquid evaporation, lime kiln modifications
Long nip press, impulse drying, and other advanced paper machines
Improved boiler design/operation (cogeneration), and distributed control systems

Cement
Improved grinding media and linings, roller mills, high-efficiency classifiers, wet process slurry
Dewatering with filter presses
Multi-stage preheating, pre-calciners, kiln combustion system improvements, enhancement of internal heat transfer in kiln, kiln shell loss reduction, optimize heat transfer in clinker cooler, use of waste fuels
Blended cements, cogeneration
Modified ball mill configuration, particle size distribution control, improved grinding media and linings, high-pressure roller press for clinker pre-grinding, high-efficiency classifiers, roller mills

Source: Worrell et al. 1997a.