10.1007/s12541-009-0107-z

Energy Consumption Reduction Technology in Manufacturing – A Selective Review of Policies, Standards, and Research

Cheol-Woo Park[1], Kye-Si Kwon[2], Wook-Bae Kim[3], Byung-Kwon Min[4], Sung-Jun Park[5], In-Ha Sung[6], Young Sik Yoon[7], Kyung-Soo Lee[4], Jong-Hang Lee[1] and Jongwon Seok[8,#]

1 Dept. of Mechanical Engineering, Korea Polytechnic University, 2121, Jeongwang-dong, Siheung, South Korea, 429-793
2 Dept. of Mechanical Engineering, Soonchunhyang University, 646, Eupnae-ri, Shinchang-myeon, Asan, South Korea, 336-745
3 School of Mechanical Design Engineering, Korea Polytechnic University, 2121, Jeongwang-dong, Siheung, South Korea, 429-793
4 School of Mechanical Engineering, Yonsei University, 134, Shinchon-dong, Seodaemun-gu, Seoul, South Korea, 120-749
5 Dept. of Mechanical Engineering, Chungju National University, 72, Daehang-no, Chungju, South Korea, 380-702
6 Dept. of Mechanical Engineering, Hannam University, 133, Ojeong-dong, Daedeok-gu, Daejeon, South Korea, 306-791
7 Dept. of Mechanical Engineering, Konyang University, 26, Naedong, Nonsan, South Korea, 320-711
8 School of Mechanical Engineering, Chung-Ang University, 221, Heukseok-dong, Dongjak-gu, Seoul, South Korea, 156-756
Corresponding Author / E-mail: seokj@cau.ac.kr, TEL: +82-2-820-5729, FAX: +82-2-3280-9982

KEYWORDS: CO_2 Emission, Efficiency, Energy, Greenhouse Gases (GHG), Manufacturing, Productivity

Research on the improvement of efficiency in the manufacturing industry is underdeveloped partly because of the ambiguous objectives of the technical development of efficiencies in terms of energy consumption reduction. Consequently, the technical development of high-efficiency techniques that consider the whole manufacturing system is rarely addressed in industrial research. For this reason, this report aims to find the patterns in, and the definitions of, the technologies that will lead to efficiency improvement in the entire manufacturing industry by thoroughly investigating the literature about energy consumption reduction strategies, energy policies, and the state-of-the-art for energy-saving methods that are being pursued currently in several major countries. Through this study, the necessity and importance of the foregoing three items have been identified, and a way of defining the productivities of an energy-saving manufacturing system distinct from those of conventional manufacturing systems was attempted. It is also shown that the development of energy-saving and energy-harvesting technologies for all industrial sectors has emerged as a herald of economic growth in the near future.

Manuscript received: October 21, 2009 / Accepted: November 11, 2009

1. Introduction

Because of the continuous worldwide depletion of natural resources, the prices of resources and energy production are increasing faster than those of the essential goods of life, such as foodstuffs. Moreover, the rate at which energy prices increase is expected to become much higher than that of other resources. In addition, as a result of the climate change convention and the subsequent Kyoto protocol of the United Nations framework convention, regulation of carbon dioxide emissions has been imposed on each nation, which has become a strong factor in the manufacturing industry for reducing energy (particularly electric energy) and for encouraging competition in setting manufacturing prices.

Worldwide research is in a sharp transition in adjusting to these global trends. For instance, it was recently announced in Korea that the green-energy industry is central to economic growth, and research is branching out in the following three directions: i) the development of new energy sources that do not emit greenhouse gases, ii) the development of technology for clean fossil fuels, and iii) the improvement of machining and process efficiencies for manufacturing. Of these three directions, the first two directions are relatively clearly defined, such that financial support for the research areas related to these directions can be focused on actively conducted research. However, research about how to improve efficiency in manufacturing systems is underdeveloped because no clear definition of the objectives for the technical development of the efficiencies has been established. This may be caused by obscurity in the definition of an improvement in productiveness. As a consequence of this fundamental vagueness, the technical development of particular machine modules for the improvement of energy efficiency is addressed quite frequently, whereas the technical development of overall manufacturing system efficiency is hardly addressed in industrial research.

Manufacturing is recognized as a very important subsector in industry. The continuous increase of productivity in this sector has balanced the overall economy's productivity.[1] Although electric energy consumption reduction is very important in Korea, where the manufacturing industry relies heavily on exports, it is unfortunate that such research fields are not involved in national green growth strategies. We believe that this problem is due mainly to the lack of a clear distinction, both technically and academically, between the technical innovations of machinery that comprise the manufacturing processes, such as machine tools, and the technical improvements of productivities from the perspectives of energy efficiency. Furthermore, we believe that the concrete establishment of an academic concept of design with (electric) energy consumption reduction is very important in order to create a basic understanding by which to educate engineers in this field, who will eventually design the high-efficient manufacturing facilities and processes that will foster competitive strength in very near future.

In this report, we attempt to emphasis the necessity and importance of proper energy saving strategies, explain energy policies, and describe the state-of-the-art of energy consumption reduction as pursued in several major countries such as those in the European Union, North America, and Japan. In addition, we attempt to find patterns on the research directions and thus find a way of distinguishing the technology development of energy consumption reduction from that of productivity improvement in the manufacturing industry.

2. Energy Structure in Manufacturing

The manufacturing industry in the US, EU and other international countries is being challenged to improve its energy efficiency and reduce its carbon dioxide emissions by revolutionizing its production processes and technologies. These challenges naturally create opportunities for new business fields related to the demand for low carbon and energy efficient products and processes. In the UK, the immediate focus of the strategy to support and remove barriers to investments in these new fields focuses on three key technological areas of manufacturing activity. These include the supply chains for nuclear and renewable energy equipment and low carbon vehicles.[1]

Since 1970, the primary energy production has grown worldwide by 84 % in 2000, when the energy generated from fossil fuels constituted the largest share (about 85 %) of total energy produced, as shown in Fig. 1.[2] The reason for the dominant use of fossil fuels is that they are relatively inexpensive, abundantly available, and convenient to use. In particular, the US consumes about 25% of worldwide energy use though it has less than 5 % of the world's population, as shown in Fig. 2.[2] Of this energy consumption, 33 % is used by the industrial sector, of which the manufacturing sector accounts for about 73 % (see Figs. 3 and 4).[2]

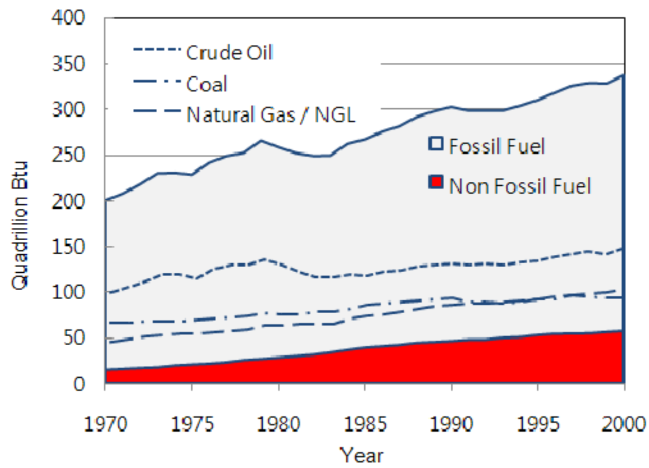


Fig. 1 World primary energy production 1970-2000

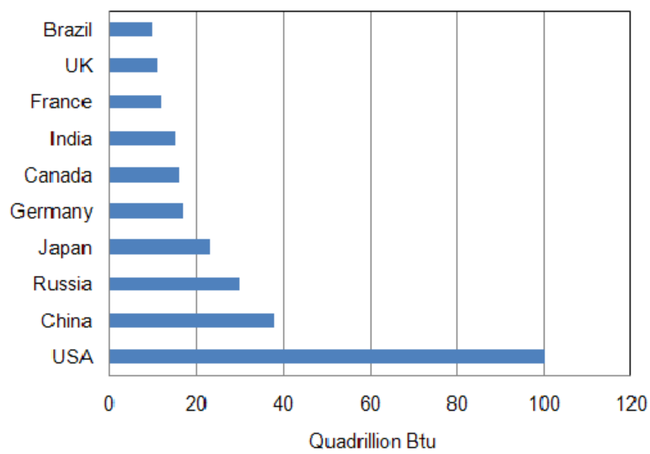


Fig. 2 Energy use by geography

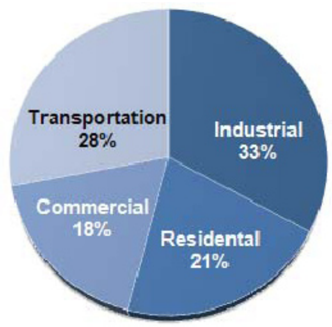


Fig. 3 U.S. energy consumption by sector in 2004

More than one-third of the energy consumed in the United States is attributed to industrial use,[2,3] as shown in Fig. 3. This sector includes the manufacturing subsectors. The energy consumption of all manufacturing subsectors in the United States is shown in Fig. 5.[4] This figure shows that one of the most significant subsector directly related to the manufacturing industry, except the fuel- and chemical-related industries, is primary metals processing, which takes up about 10 % of all manufacturing energy consumption. Thus, CO_2 emissions from the manufacturing industry originate partly from plant operations through the use of electricity and fossil fuels and from the inherent use of supplier-delivered primary metals.

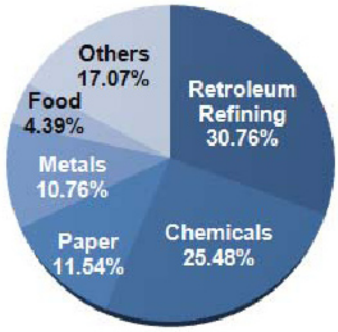


Fig. 4 U.S. manufacturing energy consumption in 1998

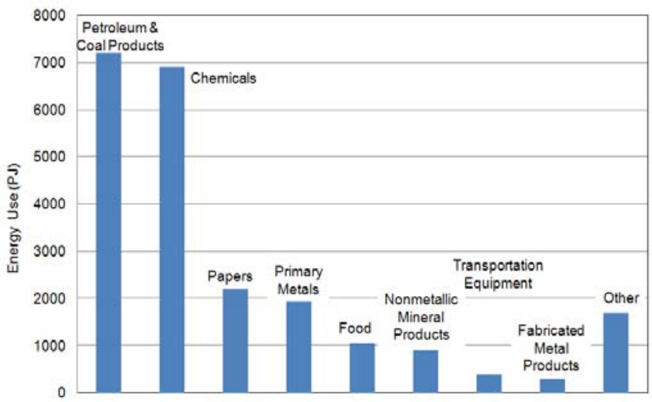
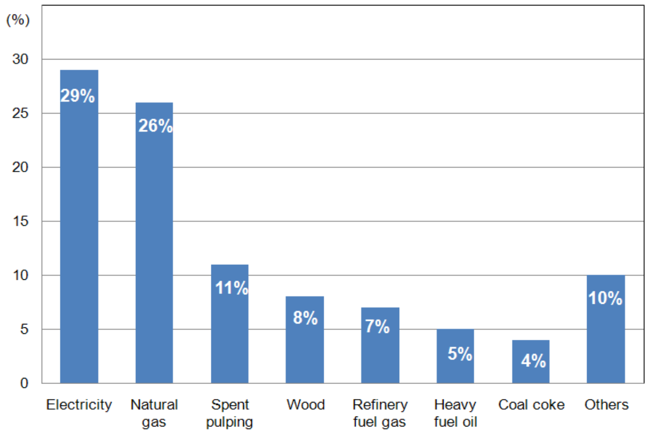


Fig. 5 Energy consumption for U.S. manufacturing subsector

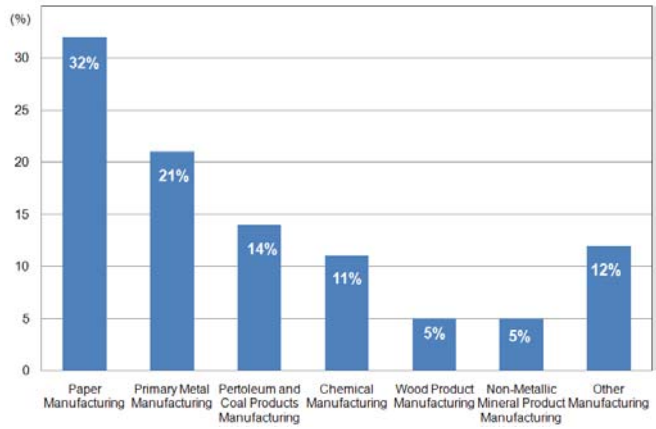
The main role of energy in manufacturing, the major factors influencing industrial decisions, possible barriers to energy efficiency, and some tactics for industrial energy management are addressed in Ref. [3] in great detail, with illustrations (case studies) applied in industry.

The statistical data on energy use in the manufacturing sector in Canada between 1995 and 2005 are collected from Statistics Canada.[5] This report reveals that the most common energy sources used were electricity and natural gas in 2005 and that 88 % of the energy consumption in this sector is conducted mainly by six major energy consuming subsectors (see Figs. 6(a) and 6(b)). As in the US, the primary metal manufacturing sector accounts for a large portion of this sector in Canada.

Manufacturing processes tend to have inevitable environmental effects. Because of worldwide climate crisis, such impacts have become the focal point of the manufacturing industry. In particular, universal measures of environmental impacts such as energy, water, and material consumption in the manufacturing processes have been accurately estimated. The specific electrical energy requirements for a wide range of manufacturing processes are examined in an energy framework.[6]



(a)



(b)

Fig. 6 (a) Share of energy use in the manufacturing sector in Canada by energy type (2005), (b) Share of energy use in the manufacturing sector in Canada by subsector (2005)

3. Energy Policies

3.1 Energy management standards

In February 2008, the International Organization for Standardization (ISO) approved the establishment of a new project committee (PC242-Energy Management) appointed to develop ISO 50001, the new ISO management system standard for energy, which is expected to be released in 2010.

The ISO 50001 energy management standard is an international framework for industrial plants or entire companies to manage energy, including all aspects of procurement and use. Conformity with the energy management standard will demonstrate that the plant or company has sustainable energy management systems in place, has completed a baseline survey of energy use, and has made a commitment to the continuing improvement of its energy performance. This standard is being written to be compatible with current management system standards such as ISO 9001 (quality management) and ISO 14001 (environmental management) – standards that are used widely throughout the world.

This standard includes energy efficiency, energy performance, energy supply, procurement practices for energy using equipment and systems, and energy use. It also mentions measurement of current energy usage and the implementation of a measurement system to document, report, and validate continual improvement in the area of energy management.

ISO 50001 is expected to provide organizations and companies with technical and management strategies to increase energy efficiency, reduce costs, and improve environmental performance. On the basis of its broad applicability across national economic sectors, it is estimated the standard could influence up to 60 % of the world's energy demand.

3.2 National policies for energy saving in manufacturing

3.2.1 European Union (EU)

The bases of the European energy policy can be summarized as the competitiveness, sustainability, and security of supply energy, as reported in *An Energy policy for Europe* in January 2007.[7] To enact this policy, the European Union set up the Strategic Energy Technology Plan (SET-Plan) to bring about new energy innovations and reduce greenhouse gases.[8] The plan aims to reduce greenhouse gas emissions by 20 %, ensure 20 % of the renewable energy sources in the EU, and reduce EU global primary energy use by 20 % by 2020. As short-term objectives, empirically validated research and positive measures for increasing energy efficiency, integrating renewable energy sources, and developing alternative fuels have been the focus. Longer-term objectives include the development of a new generation of low-carbon technologies, which is being planned to change the future energy paradigm. In the SET-Plan, reducing energy consumption and eliminating energy wastage are emphasized strongly because greatly influence the competitiveness of the EU economy, the security of the energy supply, and CO_2 reduction. The EU now proposes policies of minimum energy efficiency standards and rules on labeling products, services, and infrastructure. Specifically, an official framework for energy end-use efficiency and energy service, which includes an energy reduction target for each European country, obligations on national public authorities about energy reduction and energy efficient procurement, and steps to increase energy efficiency and energy service, has been established.[9] The framework includes self-regulation for energy-saving by industries

Table 1 Large energy using the product list and priority set by the Working Plan of the EcoDesign Directive 2008[11]

Rank	Product group	Total energy (GER, PJ)	Priority
1	In-house networking (LAN) and data processing, storing and providing equipment	31227	A
2	Transformers	17695	A
3	Tool machines (manufacturing-industrial use)	17475	A
4	Electric and fossil fuel heating equipment	14383	A
5	Surgical, patient recovery and healing equipment	8395	A
6	Industrial and laboratory furnaces and ovens	5934	A
7	Domestic equipment for clothes caring and others	4206	A
8	Automatic and welding machines	3446	A
9	Electro-diagnostic apparatus	2621	A
10	Network equipment for all types of data processing (data, telecommunication, internet, mobile and radio network equipment)	2469	A
11	Power electronics products (inverters, static converters, inductors, soft starters)	1644	A
12	Sound and image processing machines and equipment	1575	A
13	Food preparing equipment, domestic and household use	1324	A
14	Refrigerating equipment	915	A
15	Air condition systems and heat pumps	813	A
16	Electromechanical hand tools	723	A
17	Measuring transformers	682	A
18	Aerials, antennas, radars, radio navigation and control systems	487	A
19	Lifting, moving and loading equipment	263	A
20	Cashiers and ticketing machines	254	A
21	Sound processing machines and equipment (including radio equipment)	242	A
22	Other motors or motor driven equipment not covered by lots and the above categories	140	A
23	High energy diagnostic and healing equipment	124	A
24	Lighting installations not covered by existing lots	121	A
25	Food production equipment	114	A
26	Vending machines for beverage and goods	104	B
27	Compressors	88	B
28	End equipment for data use and communication with option of net connection	77	B
29	Motor driven equipment for waste water process, hot water and chemical process	69	B
30	Machines for personal care	49	B
31	Ventilation equipment for underground infrastructures and special processes	18	B
32	Mowers	13	B
33	Boilers		B
34	Generating sets using fossil fuels		B

and the application of minimum requirements with regard to energy performance in buildings and industry. In particular, the Ecodesign Directive, adopted by the European Parliament and the Council in July 2005, is a prominent policy.[10] EcoDesign is meant to improve the environmental performance of products throughout their life-cycle by systematically integrating the environmental aspects at the initial stage of the product design. The EcoDesign Directive applies to all energy-using products (except for vehicles for transport) and covers all energy sources. Manufacturers who begin marketing the energy-using product covered by the Directive in the EU area have to ensure that it conforms to the energy and environmental standards as set out. Since earlier Directives for minimum energy performance standards already contain efficiency requirements for certain products, these are to be integrated into the EcoDesign Directive framework. To implement these measures, during 2005-2008, the priorities of energy-using products were examined with a focus on over 600 products through a preparatory study, stakeholder meetings, and various other activities. In the final report, the *Working Plan of the EcoDesign Directive 2008,* written by the European Commission, 34 product groups were chosen as exemplary products in the consideration its designers evidenced for the environmental effects created by these products, including the material and energy consumption in their manufacture and use.[11] The presented product groups and rank of each product are shown in Table 1. It is noteworthy that machine tools are mentioned as one of the top three priorities for the product categories to be regulated in the framework, and it is suggested that the energy efficiency of manufacturing systems and processes may be regulated legally as well as play an important role in the products' success in the EU market.

3.2.2 Japan

The fundamental principles of Japan with respect to energy supply and demand are based on three considerations: 1) securing a stable energy supply; 2) reducing CO_2 to counteract global warming; and 3) using market principles according to a stable energy supply and environmental compliance, which were set forth in the Basic Act on Energy Policy, established in June 2002.[12] In the law, the Act sets as its main objective the establishment of sound energy security, while addressing environmental conservation and high-energy efficiency. Since global energy affairs and markets change rapidly, the Japanese government had to take a more strategic approach to energy problems in order to prepare for the future. To that end, the New National Energy Strategy was initiated in May 2006. The new Strategy has five important objectives: 1) improvement of overall energy efficiency (30 % improvement in energy efficiency by 2030); 2) diversification of transport fuels (reduction of oil dependence in transportation to around 80 % by 2030); 3) promotion of new energy development and introduction (reduction of oil dependence over primary energy supply under 40 % by 2030); 4) increase of nuclear energy and secured energy utilization (increase of the ratio of nuclear power to all power production from 30 % to 40 % or more by 2030), 5) stable supply and clean use of fossil fuels (increase the oil volume ratio in exploration and development by Japanese companies to around 40 % by 2030).

In Japanese energy policy, energy reduction is regarded as the most important factor, and related activities were initiated in Japan earlier than in any other country. After the first oil crisis, Japan established the Energy Conservation Law (a law concerning the rational use of energy), and it became a long-standing and respected basis for Japanese energy conservation policies.[13-15] Thorough efforts have been made for voluntary energy management, improving the efficiency of energy-consuming equipment in the private sector according to the Energy Conservation Law. Introducing and dispersing energy-saving equipment and/or systems and active measures for the development of energy-saving technologies are performed in three major energy-consuming sectors: industry, commercial/residential, and transportation. Although manufacturing is not considered as a separate sector, it is a common and basic field and under the law's purview. In the industrial sector, plan-based and voluntary energy control should be thoroughly and strictly managed in accordance with the Energy Conservation Law in manufacturing factories or business establishments, which use annually 1500 kiloliters in crude oil equivalent or more for heat and electricity. These factories and business establishments should submit periodic reports on the use of energy, submit mid- and long-term plans for measures to achieve energy conservation targets, and appoint energy managers in accordance with the law. In addition, policymakers have strongly encouraged private industries to introduce functional facilities to improve energy efficiency, which is also an effective measure against global warming and oil price variation. The law stipulates energy conservation standards for domestic appliances and vehicles according to the "Top Runner". Manufacturers and other entities are obliged to comply with the standards. "Top Runner" standards, such as fuel economy standards for vehicles and energy conservation standards for electric appliances, should be set exactly the same as or higher than the best standard value of each product item currently available in the market. It currently covers 21 product categories, including passenger and freight vehicles, air conditioners, televisions, refrigerators computers, and electronic heaters.

To meet the 2030 energy efficiency target set by the New National Energy Strategy, the Japanese government considers energy efficiency in the manufacturing area indispensable. Therefore, a wide range of themes relevant to and supportive of manufacturing has been being suggested in various R&D plans. For example, super-combustion system technology (e.g. glass manufacturing technology using plasma technology) and future energy-conserving device technology (e.g. energy conservation technology for transformers and motors using SiC) are key priority technological fields in the "Energy Conservation Frontrunner Plan," which is intended to establish technological innovations through inter-industry and inter-research field cooperation.[13,16] In addition, new manufacturing processes are considered as a priority for future ecological and economical groups in the "Strategic Technology Map," which is formulated and revised annually by the Japanese government.[17]

3.2.3 North America

The National Energy Policy (NEP), released in 2001, is the final report of the National Energy Policy Development Group (NEPDG). The report describes five goals for the current presidential administration: modernizing energy conservation, modernizing the energy infrastructure, increasing energy supplies, increasing environmental protections, and increasing the nation's energy security. The NEP states that the best way to meet the goal of modernizing energy conservation is "to increase energy efficiency by applying new technology—raising productivity, reducing waste, and trimming costs."

In March 2009, Vice President Joe Biden announced plans to invest $3.2 billion in energy efficiency and energy conservation projects in the United States. The Energy Efficiency and Conservation Block Grants program, funded by President Obama's American Recovery and Reinvestment Act, will provide grants for projects that reduce total energy use and fossil fuel emissions and improve energy efficiency nationwide.

DOE and the U.S. Environmental Protection Agency (EPA) have released an updated version of the National Action Plan for Energy Efficiency, "Vision for 2025: A Framework for Change", which lays out a proposed energy efficiency action plan for state policy makers. The updated action plan encourages investment in low-cost energy efficiency programs and shows the progress that the states are making toward their goals, while identifying areas for more advancement.

The Industrial Technologies Program (ITP) is the Department of Energy's (DOE's) industrial energy efficiency program, which provides federal support for industrial R&D for energy efficiency technologies. The mission of the ITP is to decrease the energy usage of the U.S. industrial sector through a coordinated program of research and development, validation, and dissemination of energy efficiency technologies and operating practices. The ITP aims to invest in high-risk and high-value R&D that has the potential to reduce the energy requirements of an industry where market barriers prevent adequate private-sector investment. Because energy is such an important input for many manufacturing industries, reducing energy requirements can lower energy costs, reduce greenhouse gases and other emissions, and improve productivity per unit of output. The ITP program's goals are to contribute to a 25 % decrease in energy usage by 2020 and to commercialize more than 10 industrial energy efficiency technologies between 2003 and 2010.

The U.S. Council for Energy-Efficient Manufacturing (U.S. CEEM) was recently formed to develop and implement the Superior Energy Performance (SEP) initiative. SEP provides industrial facilities with a road map for achieving continual improvement in energy efficiency while maintaining competitiveness. Its goal is to reduce industrial energy usage by 25 % over the next decade. The main elements of SEP are energy management standards, system assessment standards, and measurements and verification protocol.

4. Energy-Saving Technology

4.1 Measurement of energy efficiency and its applications

Manufacturing is closely connected to natural resources, and industrial companies are large consumers of the primary sources of energy. Increasing energy prices, ecological relevance, and legislative pressure have brought the energy consumption of manufacturing to the attention of industrial companies. Hence, it is now important for these companies to develop an energy consumption model, measure energy efficiency, and forecast energy consumption. This section presents a set of studies and efforts[18-23] to increase the energy efficiency in manufacturing processes.

The energy consumption in Germany industry, including manufacturing industry, is analyzed.[18] Studies on machine tools have shown that the power savings potential is 10-25 % through the reduction of the time used waiting or in the start-up mode. Moreover, better quality control systems can minimize errors and the use of resources.

These tendencies can also be shown in other industrialized countries. The energy demand of American industries is more than one-third of all United States energy consumption.[3]

By implementing only procedural and behavioral changes, industries can achieve a practical energy reduction of at least 30 % of the overall energy savings potential. A summary of the allocation of primary energy consumption is presented; primary energy input, central energy plant, energy distribution, energy conversion, and energy are applied as process work. Only 43 % of manufacturers' energy inputs are applied to process work, and 57 % are lost or diverted without the intended process activities. Some manufacturers, like the Ford Motor Company, have found ways to do useful work that have benefits unrelated to energy savings, such as reduced raw material waste, water consumption, and maintenance or repair.

Using experimental data and Response Surface Methodology, it is possible to conduct statistic modeling of machine tool efficiency and of specific consumed energy in machining as a function of different working parameters.[19] Experiments were carried out to measure the machining parameters of machine tools and the power consumed by the electric motor. From this model, the amount of the mean economic specific-energy consumed can be determined for a given amount of material. For example, consumed power energy can be reduced by increasing the feed per tooth in a vertical-milling process.

However, this model cannot be easily applied to other machining processes and machine configurations. Dietmair et al.[22] have introduced a generic model for the energy consumption behavior of machines. Successful forecasts of energy consumption and optimizations of machines for minimal energy consumption under a given application scenario have been demonstrated with this model. A number of component and operational case studies have been conducted to determine how this model can be used for energy efficiency analysis and optimization tasks.

By focusing on the interdependencies and dynamics of all technical processes, an integrated chain concept is presented to foster energy efficiency in manufacturing companies for different layers (e.g. input, logic, user and evaluation layer).[23] In addition, a holistic five-step approach to increasing energy efficiency has been developed: production process chains, energy analysis of production, energy analysis technical building services, load profile and energy costs/energy supply contract analysis, and integrated simulation and evaluation of production systems. Finally, the proposed approach is applied to a German SME.

4.2 System and simulation approaches

Because calculating energy consumption in a manufacturing system using a simple mathematical model is difficult, system engineering approaches have been developed to model the energy flow and to improve the energy efficiency in manufacturing systems.

Wolters et al. broke down a production system into three types of processes: (1) The transformation subsystem that transforms raw material into a product using energy; (2) the utility subsystem that transforms energy into a proper form for production; and (3) the heat recovery subsystem that recovers residual heat energy.[24] In using the subsystem models, various production system design sequences – for example, determining whether the transformation subsystem must be designed before design of the utility systems, which are based on the transformation subsystem, and so on – have been compared. The proposed method was demonstrated by using a production system retrofitting and cases of complete rebuilding. When six different design sequencing strategies were compared, the results showed that there is an optimal strategy to ensure optimal energy efficiency for a given situation.

Similarly, Hermann and Thiede introduced a holistic approach to analyze the economic and ecological objectives.[23] This study focuses on the optimization of the process chain with the objective of securing the best electric energy efficiency using a simulation. The production plant is modeled as a complex system composed of three subsystems: (1) Production system (machines and operators); (2) technical building services (TBS); and (3) a building shell. With the proposed subsystems, a production plant is modeled as a dynamic complex control system that involves inputs, outputs, and internal variables, such as energy, material, local climate, and waste heat and material, among other factors. The study proposes a five-step approach using a simulation model: (1) Analysis of production process chain; (2) Energy analysis of production and its equipment; (3) Energy analysis of technical building services; (4) Load profile and energy cost/energy supply contract analysis; (5) Integrated simulation and evaluation of the production system. They have developed simulation software because existing manufacturing system simulation tools cannot conduct energy consumption analysis. The developed simulation software was applied to optimize automotive component production to achieve the best electric energy efficiency.

4.3 Smart grid for manufacturing

The concept of power grids has evolved to include the integration of new information and communication technologies, armored by high-level intelligence, with power transmission lines and distribution cables branching out from the United States and the European Union to the whole world. In particular, because of the gradual movement towards SmartGrid enforcement, electric utilities are forced to incentivize electricity customers to use electric energy in different ways at peak times on demand. To date, most demand response efforts in North America have been coordinated with larger users of energy – commercial and industrial users.[25] A secure device management protocol mainly targeting the BPL (Broadband over Power Line) network is also proposed in Ref. [26], where management patterns are inspired by the SmartGrid concept.

GridWise™ and SmartGrid are the two most representative focusing projects for developing future intelligent power grids in the US and European Union. Background information, such as the current situations, politico-economic contexts, resources, power infrastructures, and energy policies of the two world powers that have developed these representative approaches, is treated in Ref. [27]. The similarities and differences of these two visions, not only in the abovementioned industrial and political areas, but also from the research perspective, are also presented in this work. More specifically, both approaches basically have a similar technological and conceptual objective. However, they exhibit different traits in the role of distributed generation for future electrical energy security. The GridWise™ testbed is shown in Ref. [28], in which digital technology, dynamic pricing, and customer-driven control are employed to conduct decentralized coordination of electricity use that can achieve enhanced reliability, increased capacity utilization and higher customer satisfaction. Furthermore, the SuperSmart Grid approach that combines wide-area power generation and decentralized power generation is proposed in Ref. [29], wherein renewable power generation is proposed as a viable contributor, both technologically and economically, to energy security, climate security, social security, and national security.

The relevance of possible options and challenges in applying such approaches has been widely investigated in the United States,[27] European countries,[27] New Zealand,[30] and North-eastern Asian countries such as Korea,[31,32] China and Japan.[33] Korea has unveiled an ambitious plan to be the world's first country to convert its electricity network into a smart grid.[31] The Korean government, according to Ref. [32], is preparing to launch a major smart grid initiative to create a huge market.

Though introduced very recently, the SmartGrid or GridWise™ concepts are now being employed in industries that include manufacturing process engineering. For instance, in order to ensure viable small scale on-site distributed generators for micro-grids and smart grids, micro-turbines under islanded and grid-connected modes of operation at distribution voltage levels are examined and analyzed in Ref. [34].

4.4 Recent research trends

4.4.1 European Union (EU)

4.4.1.1 High-temperature Industry

The European commission (EC) supports various R&D plans to develop new energy technologies that increase efficiency and bring new technologies to the market. The EC via the Directorate DG

XVII for energy has been carrying out programs such as JOULE, THERMIE, BRITE-EURAM, SAVE and ALTENER.[35] These programs focus on researching variable energy technologies that target GHG (Greenhouse gas) emission reduction. In particular, in the program THERMIE, energy-saving technology for high-temperature industry fields, such as ceramics, glass, cement, baking, plastics, steel industries, has been actively developed. Christos et al. (2001) introduced new energy-saving technologies according to different ceramic production process levels, and thermal and electrical energy-savings results from implementing newly developed technologies, which were developed in European ceramic sector, have been described quantitatively.[35] In particular, the energy efficiency improvement-focused research results of firing, the most energy intensive stage, have been reported. Worrel et al. (1995, 2000) introduced methods to diminish the amount of energy consumption, CO_2 emission, and an economical analysis of the lifecycle of products to attain high plastic production efficiency.[36,37] Examples of energy-saving technologies in the area of packaging have been introduced, and a quantitative energy decrement was suggested by comparing them with existing technologies. Behrens et al. (2008) introduced a warm-forming technology, which improves on conventional hot-forging technology used in the steel industry.[38] Semi-hot or warm-forging technology is a low-temperature process used to manufacture long flat pieces. One advantage of this technology, which reduces energy consumption, is its improved effect on surface roughness and closer tolerances, which are achieved by decreasing the forming temperature.

4.4.1.2 EU Framework Programme

The seventh framework programme (FP7) for research and technological development establishes the basis for creating cost-effective technologies for a more sustainable energy economy for Europe and ensuring that European industry can compete successfully on the global stage. FP7 works during 2007-2013, and a EUR 2.35 billion budget has been allocated to non-nuclear energy research.[39] The objective of the research projects in FP7 is to make energy production and consumption patterns sustainable and secure. This contributes to decreasing dependence on imported fuels and to producing a range of different energy sources such as hydrogen and natural sources like solar or wind energy. FP5 and FP6 include energy issues, of course, to ensure that the European industry is internationally competitive.[40] In 2010, manufacturing R & D associated with energy will be fully activated. In November 2008, the EC proposed a public-private partnership (PPP) configuration to support economic recovery in Europe. From 2010 to 2013, this project will provide EUR 3.2 billion to key industries: manufacturing (Factories of the Future), construction (Energy-efficient Buildings), and the automotive (Green Cars) sector.[41] In particular, the Factories of the Future Public Private Partnership (FoF PPP) project in the manufacturing sector will be supported by EUR 1.2 billion, and various research studies on green production, such as energy efficiency and reduction, environmental impacts, cost, productivity, and performance will be carried out to develop sustainable manufacturing, ICT-enabled intelligent manufacturing, high-performance manufacturing, and manufacturing processes to handle new materials technology under NMP (Theme 4, Nanosciences, nanotechnologies, materials & new production technologies) and ICT (Theme 3, Information & communication technologies), which are some of the 10 themes of FP7.[42]

Energy-related research in the production and manufacturing industries in Europe are carried out briskly through R & D activities under the *New Production* section of the latest framework programme, FP6 and FP7. Research studies are trying to improve competitiveness and sustainability and develop the industrial systems of the future, which can result in benefits such as cost-effective, high-quality, eco-friendly, and more flexible manufacturing systems. In particular, FP7's objective is a transition from a resource-intensive to a sustainable knowledge-based industrial environment in EU.[40] In other words, from 2007, research on energy and the environment has been more active than ever.

To support the FP6 project, Relux Entsorgung Gmbh & Co. KG of Germany conducted a project called *Recycling of EAF Dust by an Integrated Leach-Grinding Process (REDILP)*.[43] Research teams (2005) developed a new method of implementing high-energy ball milling for separating zinc oxide, zinc ferrite, and magnetite (at room temperature with high efficiency) from the waste electric arc furnace (EAF) dust that is generated in the steel manufacturing process. This technology is an environment-friendly process to yield a reduction in energy and costs through recycling EAF Dust. The Labor SRL (Institute for Integrated Production Hannover Ltd.) of Italy conducted a project called the *Development of a new machinery for nanotubes mass production based on the channel spark ablation technique (NANOSPARK)* with the support of the FP6 project.[44] Through the development of this device, a reduction in production costs and energy consumption and productivity improvement effects were achieved. The NODESZELOSS research team, organized by Professor Carlos Negro of University of Madrid in Spain, performed the *Novel device to study pulp suspensions behaviour in order to move towards zero energy losses in papermaking (NODESZELOSS)* as an FP6 project from 2004 to 2007.[45] Energy constitutes the highest portion of costs in paper mills. Therefore, in this project, studies on pulp suspension behaviour and the design and improvement of pipes and pumps, which are important devices in paper production process, were conducted. Through these studies, around 19% of energy costs could be reduced. The RotoFlex research team organized by Smithers RAPRA Technology of UK has been carrying out studies on "Innovative rotomoulding development to improve cycle times and process efficiency whilst facilitating greater flexibility in product design and integrity for the SME-rotomoulding sector (RotoFlex)" in 2009 as an FP7 project.[46] The core of this project is to develop an automatic feed system for rotomoulding machines and through this development achieve a 30% reduction in cycle time with 30% energy savings as its target. Additionally, research about the development of simulation software for the improvement of the rotomoulding process, and the process development for manufacturing advanced composite/multilayer products by utilizing automatic feed system are in progress.

4.4.1.3 IMS2020

Intelligent Manufacturing Systems (IMS),[47] an industry-driven international collaborative manufacturing research initiative, is currently conducting the IMS2020 Project (01/2009~12/2010).[48] The objective of the project is to build a roadmap towards establishing the IMS in 2020. The project focuses on five key areas that require international collaboration: (1) sustainable manufacturing, products and services; (2) energy efficient manufacturing; (3) key technologies (such as model-based enterprises, nano-technology, smart materials, and robotics, among others); (4) standardization; and (5) innovation, competent development, and education.[49]

The research group identifies energy efficiency as one of the most important research issues in the near future. In this project, energy efficient manufacturing is defined aiming to reduce the use

Table 2 Research Topics Proposed by IMS2020 Projects in Energy Efficient Manufacturing Areas (Adopted from IMS2020 second online survey)[50]

Research topics	Description
Energy-aware Manufacturing Processes - Measurement and Control	An effective measurement system for energy use has to be developed, followed by energy control concepts, which facilitate the evaluation, control and improvement of energy efficiency in production.
Maintenance Concept for Energy Efficiency	New maintenance concepts should improve the energy and resource efficiency of products and machines through innovative preventive measures. New evaluation concepts integrating energy efficiency calculations in maintenance need to be designed to increase the awareness of the benefits resulting from the adapted maintenance.
Energy Efficiency Improvements through Efficient Use of Raw Materials	In manufacturing, using raw materials efficiently saves costs and energy in processes such as transformation, transportation, and disposal.
Using Energy Harvesting in Manufacturing Processes	By finding potentials and developing technical solutions for manufacturing, e.g., the energy sources of sensors and controllers can become smaller or even dispensable.
Electrical Energy Operations in Off-peak Hours	Electrical energy use in off-peak hours saves costs in manufacturing. Measurement and control tools for the operators of manufacturing equipment as well as production planning methodologies need to be developed and put into practice.
Energy Efficient Particle Size Reduction	Current grinding processes have very poor energy efficiency, because only a small percentage of power is used for breaking chemical bonds of materials. New grinding concepts and technologies have to be developed.
Energy Efficient Production Management Systems	A novel framework that manages and optimizes energy efficiency with respect to production planning and control needs to be developed and implemented in enterprise control and information systems, such as Enterprise Resource Planning (ERP), Manufacturing Execution Systems, and Distributed Control Systems (DCS).
Energy Autonomous Factory	In order to reduce energy consumption and to guarantee a reliable energy supply, self-dependent energy generation according to the actual on-site demand and facilitate the use of renewable energy sources.
Green Manufacturing for future vehicles	Taking into account the interdependencies of product design and the manufacturing process, new possibilities of car-manufacturing due to new product should be analyzed and new energy efficient production concepts developed.
Advanced automation for demanding process conditions	Advanced automation and control systems for process industries with fluctuating input streams (such as raw materials, fuels, etc.) need to be developed. Besides constant product quality, energy consumption can be reduced by achieving higher throughputs and increased energy efficiency of the process.
Intelligent utilization of waste heat	Factories in process industries are point sources of low and medium temperature waste heat, which remain widely unused. A methodology for cross-plant analysis of waste heat recovery potentials, recovery technologies for optimized utilization of heat will be developed.
Product Tags for Value Chain Performance Improvement	Product related information about the in- and outputs of manufacturing allows coordinated process improvements increasing the overall value chain performance (in terms of e.g. efficiency, costs, delivery time).
Integrative Logistics Tools for Supply Chain Improvement	Local optimizations in the supply chain often lead to inefficiencies at other places. Therefore, tools to cooperate within a supply chain, to harmonize the logistics and improve the overall performance have to be found, implemented, and summarized in a tool box.
Framework for collaboration in the alternative fuel and raw material market	Waste and by-products can be used to replace raw material and fossil fuels in industrial processes. Methodologies and strategies for cross-industry and cross-sector collaboration have to be developed in order to enable increased utilization of waste.
Technological access to wastes for enhanced utilization in resource intensive industries	Enhanced utilization of alternative fuels and raw materials, derived from waste, replaces natural resources and as such reduces the environmental impact of resource intensive industries. Technological advances in pre-treatment and upgrade options are required.
Emission Reduction Technologies	Resource and energy intensive industries emit substantial amounts of green house gases and other polluting substances. Secondary emission reduction technologies have to be developed in a coordinated approach across sectors.

of scarce resources and carbon footprints by using innovative methods and technologies, because products and processes are no longer subject only to considerations of cost and quality.[49]

The project is currently conducting a survey to identify the most important trends in these key areas. The research direction listed in the questionnaires for energy efficient manufacturing is summarized in Table 2.

4.4.1.4 Other Activities

D. D'Addona et al. (2006), by using the queuing theory called Rapid Modeling Technology (RMT), Lead Time Reduction in PCB Fabrication, has performed a study.[51] In the study, the human and economic resources of a PCB manufacturing company were evaluated and optimized by using the MPX software package. Papagiannis et al. (2008) checked the initial energy loss (1-4 %), the carbon emission reduction (1.5 to 5 %), and the power reduction of investment costs (2-8 %), which can be obtained by applying the Energy Consumption Management System (ECMS) in general industrial fields.[52] Unger et al. (2008) introduced a variety of ecodesign and environmental assessment tools for electrical and electronic equipment.[53] In particular, through case studies on battery systems, eco mouse, waveguide products, appropriate tool selection and usage were determined. The use of these tools reduced the environmental impact of products and improved environmental performance. G. Campatelli (2009) claimed that in addition to developing technologies to reduce environmental effects (including energy consumption), guaranteeing sustainability, which can produce benefits for manufacturers by optimizing the process parameters, can be part of the real solution.[54] In addition, his claim was validated by optimizing the parameters of the machining process. Finally, S. Mekid et al. (2007) proposed an energy harvesting system architecture for indoor wireless sensor nodes.[55] In this energy harvesting system, which consisted of a solar panel and piezoelectricity buzzers, the generation of energy from fluorescent light and machine vibrations in a workshop with larger motors was made possible.

4.4.2 Japan

Even before details of the Kyoto Protocol were ironed out, Japan started to work on several projects with the aim of reducing energy usage to help save the environment; consequently, it became the most well-developed and well-distributed country in terms of energy-related technology in the world. This technology is not limited only to reduce the power requirements of machinery, but can also provide a solution to energy saving and waste issues in a broader sense. This technology is now regarded as environment-conscious technology.

Except for chemical and steel plants, which are the two most representative industries that require massive consumption of energy, studies for power reduction in the parts of the manufacturing industry that use only mechanical parts concentrate mainly on the process of machining, forming, and energy efficiency, which consider energy flow and factory layout design, among other things.

Many studies have tried to develop total solutions to environmental and energy problems that can be used for entire industries. For example, the manufacturing system is constructed with environment-conscious technologies including power-saving. Here, what it means by "environment-conscious technology" is an overall consideration of how to improve conventional technology in the manufacturing process, apply night power and cogeneration, and optimize facility capability.[56] It can be inferred from the foregoing sentence that although there is not much room for improvement in a single process, there may be many things to be improved for entire facilities or systems. Here, the improvement technologies for a facility include reducing unnecessary processes such as the manufacturing and transportation of intermediate materials. In addition, such facilities often use sensor information to monitor facility operation conditions continuously, resulting in an increase of the efficiency of system operations to save and reduce energy.

Toyota created a company-conscious promotion system[57] to encourage environmental and energy-saving activities in the company. To motivate energy-saving activities in each shop, they measured and visualized energy use so that all workers would feel inspired to share ideas that would reduce energy consumption. As a result, they reduced 33 % of energy consumption per sale in 2003 when compared to that in 1990 in the automotive manufacturing process.

The Rico group[58] has tried energy consumption reduction by replacing old facilities with high-efficiency facilities and incorporating innovations into the manufacturing process. For example, energy was reduced from 90kWh/day to 1kWh/day (a 99 % electrical power reduction) by changing only the conveyor line with a moving carriage developed by this company. In addition, they cut power consumption by ¼ by applying mass flow technology to the toner filling process in photocopier machines.

During machining, energy consumption reduction has been studied mainly in the following ways:

i) The active application of near-net-shape technology in machining. Basically, the electrical power and energy savings in machining can be conducted by reducing the amount of raw materials used in machining. This reduction of materials can be accomplished by setting up the product's geometric dimensions after the first-step in cutting to match closely to that of the ultimate shape.

ii) Minimizing cutting fluids in machine tools. Cutting fluids are used mainly for cooling, lubrication, and chip disposal in machine tools. However, their disposal costs tend to increase because of the corruption of cutting fluid. Semi-dry (or dry-cutting) technologies are needed to minimize the cutting fluids requiring large amounts of energy in both usage and disposal. However, because of various cutting conditions, differences in the materials to be cut, or the complexity of the parts' shapes, these technologies are applied *ad hoc* in actual machining shops.

The application of dry or semi-dry technology affects power reduction in a different way, because the friction between tools and workpieces play a key role in the use of energy in the machining process. However, this causes machining quality to decrease because of increased tool wear and adhesion. Therefore, it is essential to use coated tools[59,60] when dry cutting technology is applied in the machining process. Semi-dry cutting technologies include cold air cutting, MQL (minimum quantity lubrication) cutting, OoW(oil on water) mist cutting, and nitrogen gas cutting. In the cold air cutting process, compressed cold air at a temperature of -30℃ is supplied as a coolant. The MQL cutting[61,62] method is supposed to minimize the application of lubricant composed of a mist of a vegetable oil propelled by compressed air. In addition, OoW mist cutting[63] is supposed to use an oil film on water fog, which simultaneously increases the cooling and lubricating effects. There is a cutting method whereby liquid nitrogen is used to maximize cooling when materials that generate excessive heat are cut; nitrogen gas[64] is often used instead to prevent explosions when cutting such materials, including magnesium.

Grinding, like cutting, also consumes considerable energy because of the need for a large amount of coolant. In Japan, a research study was carried out for replacing the coolant grinding method with the dry or semi-dry method and for developing associated grinding machines in order to apply these technologies. In particular, cold-air grinding was developed in order to counteract massive heat generation during the grinding process. However, because this technology requires excessive electric power to produce cold air, ECOLOG grinding technology[65] was developed to use both vegetable oil for the lubricating effect and water-soluble coolant mist for the cooling effect.

In order to apply dry or semi-dry technologies to machine tools, it is also necessary to furnish a proper bed structure for proper chip disposal and a tool structure[66-68] to supply MQL mist to the cutting point. A small-size cylindrical grinding machine[69] was developed by simple design changes, such as the applications of MQL-grinding, linear motor driving, and the wheel shaft mechanism. This machine can reduce total electric power consumption by more than 50 %. By contrast, studies have been performed on mechanical elements requiring a considerable amount of energy consumption, such as LM-guides,[70] ballscrews,[71] and bearings[72] in order to make energy-efficient machine tools. The development of a desktop-size machine tool[73] is also an example of minimizing energy consumption in small-scale workpiece machining processes.

iii) The development of multifunctional machine tools. Most mechanical parts cannot be completed by a one-shot machining process but require instead a combination of several processes. Therefore, loading/unloading equipment and a moving carriage (such as AGV and conveyor) between machine tools are necessary. These implements often cause an increase in energy waste as the number of manufacturing processes increases. In Japan, multifunctional machine tools[74] were introduced a few years ago to carry out a reduction of redundant manufacturing processes. These multifunctional machine tools result in great energy savings, but they also cause side effects, such as a decrease in production lead-time and an increase in labor costs.

iv) Minimizing redundant operating time. Energy may be wasted because of unnecessary machine operation, even when an energy-efficient machine is used. As shown in Fig. 7, the energy consumption for one cycle of grinding consists of fixed and variable power in actual operation and in the idling time between the actual operations. Therefore, in order to reduce power consumption, several technologies have been developed, as shown in Table 3.

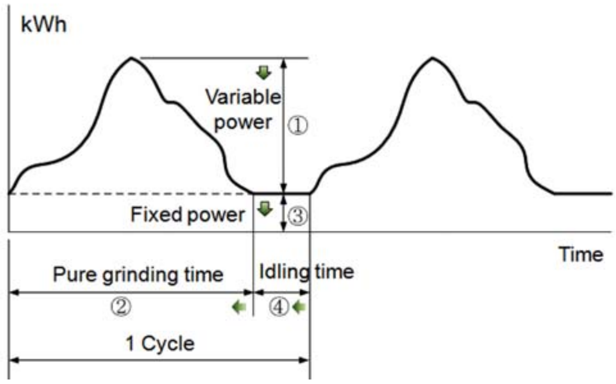


Fig. 7 Energy consumption for one cycle of grinding

Table 3 Power-Saving Technologies in Grinding Machines Via a Reduction of Operating Time

Power-Saving Parameters	Detailed Technologies
Grinding power	(1) Feeding power reduction during grinding - Weight reduction of grinding wheel carriage; optimal design by CAE analysis, application of honey-comb structures, and lightweight materials - Driving mechanism design for minimization of friction energy; application of direct driving, built-in driving, and linear driving mechanism (2)Spindle shaft power reduction during grinding
Pure grinding time	(1) Pure grinding time reduction by applying ultra-high speed grinding technologies - Increase of maximum power with a decrease of total power because of pure grinding time reduction (2) Cost reduction of disposal power using CBN wheel grinding (In conventional grinding, the disposal power increases as the abrasives, mixed with coolant, flow into the machining surface)
Fixed power	(1) Power reduction of lubrication, coolant, and air supply during one cycle (2) Fixed power reduction for maintaining actuator condition - Change of ordinary operating system (it always needs energy) with an optimal energy supplying system; intermittent or high-efficiency operation by applying an inverter motor and accumulator (it is known that up to 40 % of energy savings can be made by optimizing the coolant system).
Idling time	(1) Power-saving by a reduction of work setup time (2) High speed of loading/unloading system, and several actuators (3) Information-processing time reduction between CNC and PC

Particularly, a power-savings controller[75] has been developed to make machines efficient by controlling idealing and pure grinding times.

v) The optimal design of a factory layout to use energy most efficiently. We can reduce energy usage by optimizing the layout design of facilities,[76] which are based on energy distribution needs throughout the entire factory. These techniques include energy flow control based on a calculation of temperature distribution, so that any excessive energy can be sent to the area needing the energy by using circulating fans in the shop.

Around 30 % of consumed power can be reduced[77] by applying process reduction (such as the use of multifunctional machines) to heavy engine and turbine manufacturing plants; 62 % of standby power can be saved in machining centers; and 85 % of hydraulic power can be saved in ATCs. The main reason for such great power savings is the effects generated by operating heavy manufacturing facilities. Compressed air in a factory requires a massive amount of energy; it was reported[78] that compressor power consumption could be 30 % in an entire factory, and about 30 % of power can be saved by dropping the pressure of compressed air by 0.3MPa. One example suggests that energy loss can be minimized by applying a hydraulic intensifier when high pressure is needed. In automotive parts and home products, the forming process using a press machine is used, and this process requires lots of energy. Energy savings in this process[79] can be achieved by applying near-net-shape and multipurpose-manufacturing technologies, such as the integration of each machining process (shearing, forging, and bending, etc.).

4.4.3 North America

In the United States, research about energy saving and environment-friendly development in the manufacturing field has been performed in various ways, from the idea of cost reduction to that of reducing the environmental impacts of the manufacturing or machining processes. For instance, the energy efficiency, cost-saving, and environmental impacts of cement manufacturing industry in US has been described in great detail.[80] The assessment of current practices and needs for research in the ceramic machining industry are described Ref. [81]. As for the negative side of energy efficiency, the rebound effect, which explains the trend that the eventual gains of energy efficiencies tend to accelerate the consumption of energy and partially decrease the initial reduction of energy sources, is addressed and quantified using time series data from energy consumption in the manufacturing industry in the US.[82]

Djassemi[83] discussed the application of parametric programming to CNC machining for the purpose of identifying the potential to increase the efficiency of CNC operations. Schmitz et al.[84] described the application of high-speed milling to the production of various prototypes by attempting to reduce process times. They also identified the basic requirements for the use of high-speed milling based on a time schedule. Rakwal and Bamberg[85] demonstrated the merits of using thin electrode wires analytically from the viewpoint of material utilization in the WEDM process, which was proposed as an alternative process for the manufacture of germanium wafers. Miller et al.[86] investigated the effects of spark cycle and pulse on-time for the wire EDM of various machining materials and demonstrated the possibility of the wire EDM process for machining a few advanced materials to achieve manufacturing objectives such as a high material removal rate or high efficiency. Fox-Rabinovich et al.[87] attempted to enhance the adaptability of coatings and thus to increase the tool life of end milling cutting tools by applying ternary nitride coatings with high aluminium content to the tool surface. Kovacevic et al.[88] explored the feasibility of improving the machinability of difficult-to-machine materials by using a high-pressure waterjet as a coolant/lubricant in machining processes and addressed the merits of using the proposed cooling as opposed to flood cooling for machining such materials. Calatoru et al.[89] studied the high-speed machining of aluminum alloy, which is a growing field of research both in terms of volume, performance, and efficiency because of the increased productivity that can be achieved only by increasing the cutting speed and feed. In this work, they attempted to identify the mechanism of the catastrophic wear of WC–Co tools during machining and found certain particularities in the machining process.

The development of environmentally friendly manufacturing machines and processes, not to mention cost-effective ones,[83-88,90-92] has been a long-term issue for a fairly long time. In particular, the environmental impacts of remanufacturing have begun to draw much attention from related industries and research facilities. For instance, Marksberry[93] presented a new environmentally-friendly technology for minimizing the use of metalworking fluids (MWFs) during the machining process. Weinert el al.[94] attempted to eliminate, or significantly reduce, cooling lubricants that affect all components of a production system. Dasch et al.[95] performed an experiment to identify the mechanism underlying the dry machining of aluminium, which would have enormous benefits such as reduced infrastructure, lower costs, and a cleaner environment, compared to wet machining. Williams and Shu[96] analyzed the remanufacturer of waste streams in electrical motors, toner cartridges, valves and telephones to support product designs that facilitate remanufacture. Energy and other environmental performance measures in the original manufacturing and remanufacturing of engine components are compared, and the results are discussed in Ref. [97]. In addition, the economical advantages of remanufacturing as opposed to manufacturing have been reported in Refs. [98,99]. It has been also reported that remanufacturing energy savings reach up to 85 % when compared to manufacturing.[100] Recently, the original manufacture and remanufacture of diesel engine components have been compared, and the environmental performances and benefits of remanufacturing against manufacturing are addressed in Ref. [21].

4.5 Energy-saving technologies in non-manufacturing sectors

Because of a recent increase in energy costs and environmental regulations, new sources of energy such as wind, bio-fuels, and solar energy are now replacing conventional fossil-based energy such as oil.[101] However, the use of new energy alone has limitations as a solution to energy depletion and global warming. Hence, energy-saving technologies for increasing energy efficiency should be developed to address the current energy and environment crises.

Fig. 8 shows the overall percentage of energy consumption by economy sector. As seen in the figure, two thirds of total energy consumption is consumed by non-industrial sectors. Consequently, it is worth investigating energy-saving measures that can be used in non-manufacturing sectors. In this section, energy-reduction techniques and approaches used in the non-manufacturing section will be discussed. This non-manufacturing sector can be divided into two categories: transportation and building.[102]

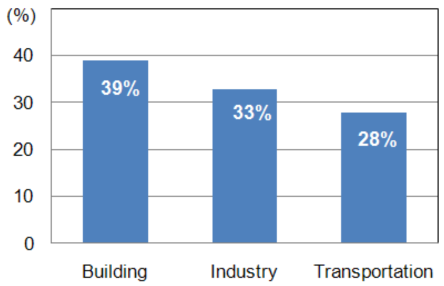


Fig. 8 Energy consumption by economy sector (Source: Energy information administration)

Many efforts have been made in the transportation sector to increase energy efficiency and reduce CO_2 emissions.[101-105] Here, the transportation sector can be divided into several sections: passenger cars, trucks, trains and airplanes.[102] In order to increase the fuel efficiency of cars and trucks, the weight of the car must be reduced. To decrease the weight of a car, new materials have to be developed, such as carbon fiber reinforced plastics (CFRP), which have high strength with light weights.[103] By reducing the weight, the energy needed for acceleration can be reduced. On the other hand, in addition to the energy consumption related to driving, there are also issues of lighting and air conditioning efficiency. Lighting and air conditioning in cars use electricity. Therefore, similar energy-saving technology used in the building and house sector can be used for efficient lighting and air conditioning in cars. Along with energy saving technology, clean energy is required to reduce CO_2 emissions. The electric car and the fuel cell electric vehicle will be replacing the current air-polluting gasoline or diesel cars.[101,103] The use of electricity is most efficient when renewable energy such as solar power is used to generate the electricity. Here, the development of a high-performance battery is very important to commercializing electric cars. One of the technical challenges in using a battery is that it takes a relatively long time to charge the battery.[103] In addition, the weight of the battery needs to be reduced because it has a relatively low energy density relative to the weight of the batteries.[103]

For trains, cleaner energy such as electricity needs to be used instead of air-polluting diesel engines. For clean energy, electricity needs to be generated from renewable power. However, generated power can be unreliable because it is generated from the sun and wind, which are sometimes irregular in providing energy. Consequently, an intelligent power-managing system technology is needed to provide electricity to electric trains.[106]

Many energy-saving efforts have been directed toward increasing energy efficiency in the transportation and industrial sectors. However, fewer efforts have been made toward the building and housing sectors, and there is room for improving energy-saving technologies in housing and building sections. As for buildings, energy issues are classified into two categories: the energy required to construct a building and the energy required to maintain a building. In this review, primarily electric energy-saving technology for maintaining a building will be discussed. The main sources of electric energy consumption in buildings are lighting, appliances, heating, and air-conditioning.[102,106] As for lighting, it has been reported that in every home lighting constitutes 25 % of electricity use; business offices use more than 60 % of their electricity for lighting.[102]

To improve energy efficiency, two approaches can be used: efficient driving methods for existing lighting devices and the development of new energy efficient lighting devices. For example, timer and sensor operations can reduce electric energy via an automatic on-off control of lights.[104] Further energy savings can be achieved via a brightness and dimmer control.[104] Finally, next-generation high-efficiency lighting devices are replacing fluorescent lighting and light bulbs. Next-generation lighting devices include light emitting diodes (LEDs) and organic Electro-Luminescence (EL).[104] In addition to lighting, heating and cooling in buildings consume a significant portion of energy.[102] The source of most heating and cooling energy in buildings is electricity. Hence, renewable energy such as geothermal and solar energy have drawn attention in the building sector.[102] To reduce the electric energy of appliances used in buildings and houses, not only energy-saving technology, but also proper regulations are necessary. For example, appliances in the U.S. are required to meet strict energy efficiency standards according to the National Appliance Energy Conservation Act, which was passed in 1987.[102] In addition, the Energy Efficient Rating (EER), which can be found on a label on the appliance, indicates its efficiency.[102] There have also been voluntary programs, such as Energy Star labeling.[107]

In this section, energy-saving technologies in non-manufacturing sectors are briefly reviewed. However, it should be noted that not only energy-saving technology, but also effective governmental policies and social consciousness and behavioral changes are essential to solve the current energy and environment crises.[108]

4.6 Miniaturization of Manufacturing System

In 1990s, Mechanical Engineering Laboratory (MEL) suggested a *microfactory* concept that is a new manufacturing system technology to achieve the greatest resource and energy effectiveness in machining as well as to minimize the environmental pollution.

Microfactory is a small part production system that is developed through miniaturization of manufacturing system and integration of the processes and control.[109] By implementing a microfactory, following advantages are attainable: (1) saving energy and material resources, (2) easier control of waste and pollution, (3) increased productivity, (4) improved portability and agile reconfigurability, (5) efficient utilization of space, and (6) reduced facility investment and running costs.[110]

Mishima et al proposed a *system efficiency index* based on process time, machine cost, operator cost, and environmental impact through efficiency analysis of a microfactory.[111] With the proposed method system, the efficiency of microfactory was compared to that of bearing production using a typical production line in a mass production system. The system efficiency index demonstrated that the microfactory was more efficient.

Kurita and Hattori developed a desktop multi-process machine.[112] The developed system was compared to conventional machine tools (milling, electrical discharge machining, electrochemical machining) in an environmental viewpoint. It was demonstrated that the desktop multi-process machine consumes less machining energy, less amount of machining fluid such as electrolyte and dielectric, and installation space.

Nakano et al developed a microfactory system for micro electromechanical systems (MEMS) with the following concepts: (1) every time and everywhere, decreasing a developing time; and (2) low energy and emission and high performance.[113] The system has four process cells that are composed of press forming, aerosol deposition, post anneal, and wiring by ink drawing. The power consumption of the proposed MEMS microfactory (8,000kWh/year) is estimated about 1/45 of conventional MEMS lithography facility (360,000kWh/year).

5. Energy Saving for Green Manufacturing

5.1 Low-carbon emissions

The massive increase in energy consumption has produced a rapid increase in the emissions of greenhouse gases (GHGs), including carbon dioxide (CO_2), and accelerated global warming and climate change. Such undesired and significant climate changes are very likely associated with increased atmospheric concentrations of GHGs, most significantly CO_2. CO_2 constitutes 95 % of emissions that come from fuel combustion and around 80 % of the potential global warming effect of anthropogenic emissions of GHGs. If the world continues on its current path of increasing energy consumption, CO_2 emissions are predicted to rise up to 43 billion tons by 2030.[114,115]

Table 4 presents worldwide carbon dioxide emissions by region and sector in 2001. It can be shown that the manufacturing industries produce considerable emissions from the electricity/heat production and transportation sectors. Total CO_2 emissions from industry were 9.7 gigatons (Gt) in 2001 and accounted for 36 % of total global CO_2 emissions.[116]

Another point to note from the table is that the overwhelming majority of CO_2 is emitted from the electricity and heat production process. This indicates that electricity consumption directly affects CO_2 emissions. Fig. 9 shows the historical and projection data of electricity consumption in worldwide industrial sectors. The data reveal that electricity consumption in world industries has increased rapidly and that in 2030 emissions will be twice the amount produced in 2003. In particular, from the data, it can be found that the increase in worldwide electricity consumption has been boosted by non-OECD countries where manufacturing industries are predicted to continue growing rapidly.

From these findings, it can be concluded that CO_2 emissions in manufacturing industries will increase continuously. Therefore, to protect the environment, the development of energy-saving or green manufacturing technology needs to be emphasized.

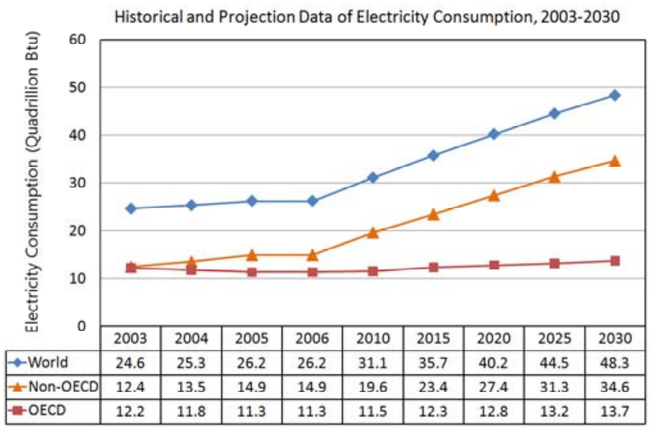


Fig. 9 Historical data and projections of electricity consumption by industrial sector (Unit : Quadrillion Btu)[115,118-120]

Table 4 Carbon dioxide emissions by economic sector in 2001[117]

	Total CO_2 Emissions (Million metric tons)	Percent of Carbon Dioxide (CO_2) Emissions by Sector					
		Electricity & Heat Production (%)	Other Energy Industries (%)	Manufacturing Industries & Construction (%)	Transportation (%)	Residential (%)	Other Commercial, Public, and Agricultural Sectors (%)
World	27,898.6	37.2	4.7	16.8	18.4	7.8	5.6
Developed	14,718.5	41.0	4.5	15.0	23.6	8.6	6.1
Developing	8,623.7	37.6	6.6	24.5	16.4	7.4	5.8
Asia	7,402.8	41.2	4.6	24.4	13.5	6.9	6.3
Europe	6,156.9	40.2	4.2	16.9	19.2	12.1	6.0
Middle east & North Africa	1,455.3	32.4	11.0	20.8	18.6	9.8	11.3
North America	6,202.3	40.9	5.2	12.0	30.2	6.4	5.2
South America	731.1	14.1	9.8	26.1	35.7	7.2	5.4
Oceania	383.9	56.7	4.9	16.0	22.6	2.0	2.5

5.2 Other environmental benefits

In general, greenhouse gases other than carbon dioxide are produced and emitted from manufacturing processes. The deleterious effects of greenhouse gases on the global environment vary from global warming, acidification, and eutrophication.[121]

Tables 5 and 6 summarize the greenhouse gas emissions of South Korea and U.S. in 2006 and 2007, respectively. The data indicate that the emissions of greenhouse gases other than CO_2 from industrial and manufacturing processes constitute a large part of total nationwide emissions. In particular, from the given data, it should be noted that most non-natural synthetic gases, such as HFCs, PFCs, and SF6, are produced from industry. These gases have a significantly greater effect, more than 10,000 ~ 20,000 times, on global warming than CO_2, as can be inferred from their global warming potentials (GWP).[122] Even a small amount of emissions of these gases can have a damaging effect on the global environment. This fact may provide another reason why energy-saving manufacturing technology is important and should be developed immediately.

Table 5 Greenhouse gas emissions in South Korea in 2006[123] (A = Total emission of each greenhouse gas, B = Manufacturing industries and construction, C = Industrial processes)

Main greenhouse gas emissions	A	B	C	Major effect on environment
Total net emission (Mt of CO_2 eq.*)	568.4	149.94	63.66	
CO_2 emission (Mt of CO_2)	542.3	149.25	27.39	global warming
CH_4 (Mt of CH_4)	1.204	0.011	0.023	global warming, photochemical oxidants
N_2O (Mt of N_2O)	0.050	0.001	0.030	acidification, human toxicity
HFCs (Mt of CO_2 eq.)	5.890	-	5.890	global warming (ozone destruction)
PFCs (Mt of CO_2 eq.)	2.874	-	2.874	human toxicity, eco-toxicity
SF_6 (Mt of CO_2 eq.)	17.818	-	17.818	global warming

* Mt of CO_2 eq.- million tons of CO_2 equivalent

Table 6 Greenhouse Gas Emissions in U.S. in 2007[124] (Unit: Million metric tons of CO_2 equivalent)

GHG	Industrial sector	Total
Carbon dioxide (CO_2)	1,760.3	6,021.8
Methane (CH_4)	497.6	699.9
Nitrous Oxide (N_2O)	313.5	383.9
Hydrofluorocarbons (HFCs)	22.0	144.9
Perfluorocarbons (PFCs)	10.1	10.1
Sulfur Hexafluoride (SF_6)	6.8	15.8
Others	-	6.1
Total Emissions	2,610.4	7,282.4

In addition, energy-saving and energy-efficient manufacturing technologies are expected to reduce energy losses and dissipation due to the friction generated at the contact interface between two moving machine parts. One major environmental issue is the disposal of used lubricating oils, since they are usually toxic and present in large volumes. About 40 million tons of oil are being produced annually worldwide. This is equivalent to the volume of water in a lake 4-km-long, 500-m-wide, and 22-m-deep.[125] A serious problem lies in the fact that some proportion of the used oil is reprocessed, but most of it is put back into the environment when it is disposed. Therefore, reducing the use of lubricating oil and cutting fluids, such as by applying MQL (minimal quantity lubrication) techniques, will be an important benefit of energy-saving manufacturing technology.

6. The Economic Aspects of Energy Saving Manufacturing

6.1 Impacts on the economy and energy resources

As stated previously, energy-saving manufacturing technologies can provide both environmental and economic benefits. The technology will reduce the use of energy resources and counteract detrimental effects on the global environment by reducing greenhouse gas (GHG) emissions.

Table 7 and Fig. 10 present the energy consumptions of some countries in recent years, including data from the manufacturing sector. Although the surveyed countries differ somewhat, the manufacturing sector generally consumes a large portion of energy, amounting to 30 ~ 50 % of total nationwide use. In particular, countries with an export-oriented industry structure such as Korea, Japan, and Norway show a relatively high energy consumption in the manufacturing sector. The data of world energy use indicate that manufacturing industries accounted for about 37 % of total energy consumption in 2006.

These data also reveal that total energy consumption depends largely on energy use in the manufacturing industry. In Canada, for instance, the manufacturing sector used 2,526.2 petajoules (PJ) of energy in 2005, according to ICE (The Industrial Consumption of Energy) estimates. If each household uses 115 gigajoules (GJ) annually, 1 PJ is approximately equal to the amount of energy consumed by 8700 households in one year. Thus, in 2005, the energy consumption in the manufacturing sector was roughly equal to the amount consumed by 22 million households in one year (nearly twice the number of households in Canada).[126]

Table 7 Comparison of energy use in the manufacturing industry in several countries and the world overall

Country (year)	Total energy consumption (petajoules, PJ)	Energy use in manufacturing industry	
		Amount (PJ)	Share (%)
Korea (2007)[126]	7195.6	3936.7	54.7
USA (2006)[127]	104,999.2	22,204.7	21.1
Canada (2005)[128,129]	8496.1	2526.2	29.7
Japan (2003)[130,131]	22,368.4	6,770	30.3
UK (2006)[132]	7,100.8	1,364.9	19.2
Norway (2007)[133]	814.0	290.3	35.7
New Zealand (2006)[134,135]	499.2	149.19	29.9
World total (2006)[135]	498,408.5	184,634.8	37.0

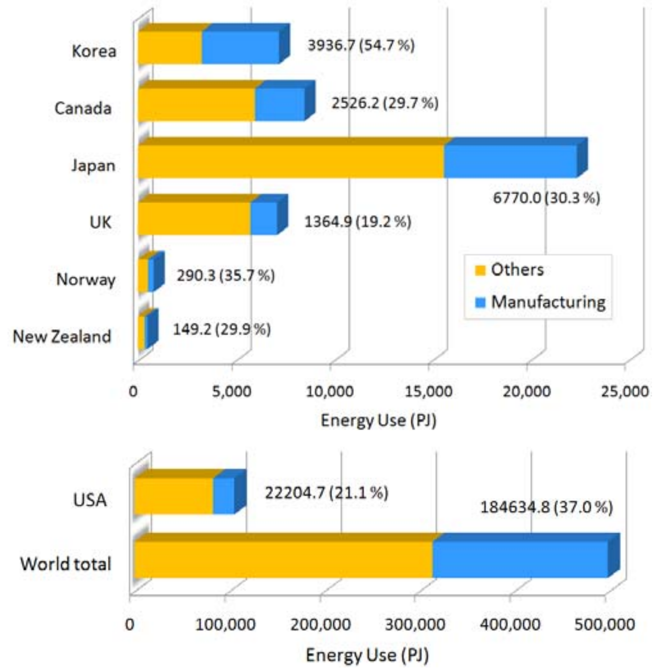
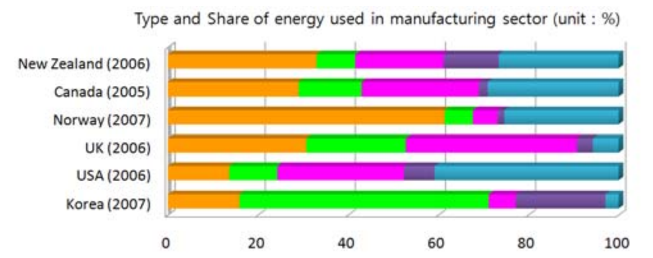


Fig. 10 Comparison of energy use in the manufacturing industry in several countries and the world overall (the data are shown in Table 7)

Therefore, the impact of energy-saving manufacturing technology on the global economy is large and will increase to meet the energy challenges that humanity faces.

The types and proportions of energy used in the manufacturing industry in each country are summarized in Fig. 11. Most countries use electricity as the main energy source for manufacturing. This finding shows that developing technology to improve the efficiency of electric energy is essential to reduce energy use in the manufacturing industry.

To estimate quantitatively the economic benefits of reducing manufacturing energy consumption, the energy prices for industry in the U.S. shown in Table 8 were used. For electricity, the price per 1 Million Btu is about 18 dollars. Thus, a cost reduction could amount to 4.7 billion dollars if 1 % of the electricity consumption in the manufacturing industry of the world (26.2 Quadrillion Btu, in 2006) [115] were reduced.



	Korea (2007)	USA (2006)	UK (2006)	Norway (2007)	Canada (2005)	New Zealand (2006)
Electricity	15.9	13.6	30.7	61.4	29	33
Petroleum	55.3	10.7	22.1	6.3	14	8.6
Natural gas	6	28.1	38	5.5	26	19.6
Coal	19.9	6.8	3.5	1.5	2	12.2
Others	2.9	40.8	5.7	25.3	29	26.6

Fig. 11 Types and proportions of energy sources used in manufacturing in several countries (unit : %)

Table 8 Energy prices by industrial sector and source in 2006 in the U.S.[136]

Energy source	Dollars per Million Btu
LPG	19.71
Fuel oil	15.33
Natural gas	7.66
Coal	3.54
Electricity	17.97

Moreover, as mentioned in Chapter 5, not only energy cost reductions, but also environmental cost reductions can be achieved by reducing energy use in the manufacturing industry, because the industrial sector has a significant impact on the global environment. Electricity generation is responsible for 33 % of GHG emissions in the U.S.[136] Most emissions are carbon dioxide (CO_2), which is released when fossil fuel feed sources are converted to electricity sources.

Table 9 shows the permit price of the main greenhouse gas (GHG) emissions in 2009. The given price data were calculated by multiplying the CO_2 emission price by the carbon dioxide equivalents of each GHG gas. When most people consider GHG emissions, they think of factories, transportation, and deforestation. Most people would be surprised to learn that the generation of electricity causes more emissions than all other anthropogenic sources. Since CO_2 emissions per 1 KWh of electricity used is 4.3×10^{-4} tons,[137] CO_2 emissions can be reduced to about 33,000 tons if electricity use is reduced by 76.8 GWh, which is equal to 1 % of manufacturing electricity consumption worldwide in 2006 (26.2 Quadrillion Btu[115]). This represents of monetary gain of 0.5 million Euro (0.7 million dollars) as a cost benefit.

Table 9 Permit price for emissions of the main greenhouse gases (GHGs) in 2009

GHG	Carbon dioxide equivalent (metric tons)	Price (Euro/ton CO_2)
Carbon dioxide (CO_2)	1	14.4*
Methane (CH_4)	23	331.2
Nitrous Oxide (N_2O)	296	4,262.4
Hydrofluorocarbons (HFC 23)	12,000	172,800
Chlorofluorocarbons (CCl_2F_2, CFC-12)	10,600	152,640
Sulfur hexafluoride (SF_6)	22,200	319,680

* CO_2 emission permit price - €14.4/ton (as of Aug. 14, 2009) [138]

6.2 Value chain of energy-saving manufacturing technology

As stated above, the manufacturing industry is the largest consumer of energy. Consequently, energy-saving manufacturing technology will be more and more important. Furthermore, despite increasing energy prices, consumption will continue to expand rapidly in the near term as a result of expanding populations and substantial economic growth in developing countries. By 2030, as shown in Fig. 12, the global demand for energy will likely be about 30 % higher than it is today – even with substantial gains in efficiency. To meet this growing energy demand, all commerciallyviable energy sources should be developed. No single source can meet the world's growing energy needs.

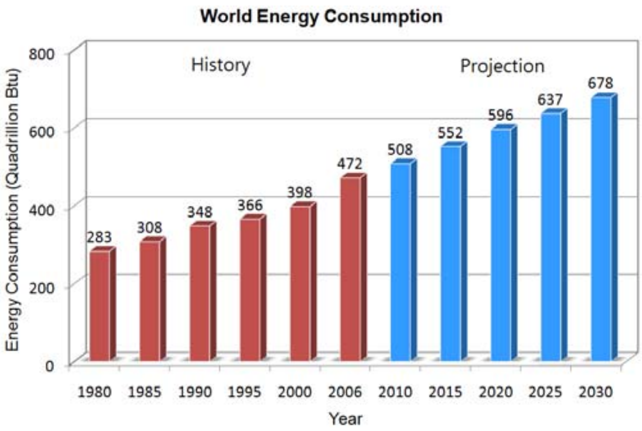


Fig. 12 World Market Energy Consumption[115]

Therefore, energy-saving and high-energy-intensity manufacturing will be indispensable as an essential technology in the near future. In fact, much research has already been initiated to develop energy-saving and greenhouse-gas-reducing technology. Table 10 summarizes some of these technologies and their impacts on the economy and environment.

Table 10 Examples of Manufacturing Technologies for Energy-Saving and GHG Emissions Reduction[104,114]

System	Technology brief	Economic effect
Refrigeration and air conditioning compressors	New air conditioning and refrigeration technology	• Reduction in electricity consumption – 221 GWh /y • Reduction in GHG emissions – 0.2 Mton/y
Boiler	Installation of the economizer allows recovery of waste heat from boiler exhaust gas	• Fuel saving effects – 115.7 kl/y •Monetary equivalent of energy savings – \$3,725,160/y
Compressor	Management of compressor delivery pressure (reduction in electric motor load by the delivery pressure reduction)	• Power saving effects – 285,000 kWh/y • Monetary equivalent of energy savings – \$4,850,700/y
Fluidic Devices	RPM control for fluidic devices	• Power saving effects – 285,000kWh • Monetary equivalent of benefits – \$326,340/y
Transformer	Electric power receiving equipment	• Annual reduction in power consumption – 170,700 kWh/y • Monetary equivalent of reduction – \$2,811,630/y
Electric motor	Use of material with strong magnetic force	• Power savings – 48,920 kWh/y • Monetary equivalent of energy savings – \$542,790/y
Lighting	Energy saving when light bulbs are replaced by LEDs	• Power savings – 2.5 GWh/y

6.3 Decomposition of energy use, intensity and their effects on environments

In order to analyze the structural changes in energy use and the consequential effects on the economies, environments, and societies of a particular country (or group of countries), it is useful to assess the active input parameters that induce such changes. The first attempt to do this analysis may be on the decomposition of economic or environmental indicators directly related to these input parameters. Thus, decomposition analysis could be offered as one of the most effective and widely used means for investigating energy consumption mechanisms and their effects on environment. The two most frequently used techniques for decomposing indicator changes at the sector level are structural decomposition analysis (SDA) and index decomposition analysis (IDA),[139] where, in general, the Laspeyres index, the base index used in IEA model,[140] and the Divisia index[141] are employed for the formulation.[142] As alternatives, the conventional[143,144] or generalized Fisher index approach[145,146] or the mean-rate-of-change index (MRCI)[147,148] could be adopted.

A decomposition study of the U.S. manufacturing energy intensity between 1974 and 1998 can be found in Ref. [149], in which a three-term decomposition of an intensity index was conducted. The manufacturing energy use in several IEA countries between 1973 and 1998 was decomposed by using Laspeyres indexes,[140,150] and the results showed that structural changes have reduced manufacturing energy use in most countries, particularly the U.S. and Japan. Consequently, structural changes in the economy and energy use in the U.S. from 1997 to 2002 were investigated through decomposition and input–output analysis (IOA) techniques.[151]

In the early 1970s, analysis focused mainly on the decomposition of energy use and intensity in the manufacturing sector, such as the study reported in Ref. [142]. However, after this period, interest started to turn to an analysis of carbon dioxide emissions, which are the main causes of global warming. A decomposition analysis using a refined Laspeyres model[152] is performed to explain changes in industrial carbon dioxide emissions and to comparatively evaluate the progress made in several EU countries for the period 1990–2003 in decoupling emissions from industrial growth.[153] A decomposition analysis of the changes in carbon dioxide emissions from passenger cars in Denmark and Greece, for the period 1990–2005, was performed[154] using a time series analysis and the logarithmic mean Divisia index I(LMD II) methodology.[141] In addition, decomposition analyses were performed to examine the variables that influence CO_2 emissions for various vehicles.[155-159]

7. Conclusions and Outlook

In this review report, we thoroughly investigated energy-saving technologies and related policies, particularly in the manufacturing industry, by focusing on the energy structure in manufacturing, energy policies and management standards in several major countries (European Union, North America and Japan), energy-saving technologies both in the manufacturing and non-manufacturing sectors, along with eco-friendly green manufacturing technologies and the impacts that these technologies have on economies and the environment. Through these investigations, we have attempted to answer what kinds of energy saving technologies will be necessary in the manufacturing sector.

Partly because of the regulations instituted to prevent climate change from causing global disasters and thus to reduce carbon dioxide emissions, and partly because of intense competition in manufacturing-related sectors, the development of energy-saving technologies has become a crucial element for survival, particularly in such industrial sectors. As could be found in many parts of this report, new technologies for energy saving and harvesting in all industrial sectors have been emerging as a major impetus for economic growth in the next generation. The worldwide share of such a trend has become a strong motive for enforcing regulations and standards on environmental development on the condition of mutual implementation as well as to foster cooperation and competition in the development of these new energy-saving technologies.

In this report, we attempted to find research trends in energy-saving measures in a few industrial sectors and consequently to find a way of distinguishing the technological development of energy consumption reduction from that of productivity improvement in the manufacturing industry, which is important to understand clearly the new direction of research in the manufacturing sector. This approach was performed by examining energy-saving strategies, energy policies, and the state-of-the-art of energy consumption reduction in several major countries. We believe that our detailed literature review of both energy consumption reduction and environment protection activities will help establish new directions for research.

ACKNOWLEDGEMENT

This work was supported by National Research Foundation of Korea Grant funded by the Korean Government (KRF-2007-331-D00035).

REFERENCES

1. The Department for Business, Enterprise and Regulatory Reform, “Manufacturing: New Challenges, New Opportunities,” 2008.
2. Evans, L. B., “Saving Energy in Manufacturing with Smart Technology,” World Energy, Vol. 6, No. 2, pp. 112-118, 2003.
3. National Association of Manufacturers, “Efficiency and Innovation In U.S. Manufacturing Energy Use,” 2005.
4. U. S. Energy Information Administration, “2002 Energy Consumption by Manufacturers -Data table,” 2002.
5. Natural Resources Canada’s Office of Energy Efficiency, “Energy Use in the Canadian Manufacturing Sector,” Cat. No. M144-164/2007, 2008.
6. Gutowski, T., Dahmus, J. and Thiriez, A., “Electrical Energy Requirements for Manufacturing Processes,” 13th CIRP International Conference on Life Cycle Engineering, pp. 623-628, 2006.
7. Commission of the European Communities, “An Energy Policy for Europe,” COM 1, 2007.
8. Commission of the European Communities, “A European Strategic Energy Technology Plan (SET-PLAN): Towards a low carbon future,” COM 723, 2007.
9. The European Parliament and the Council, “Directive 2006/32/EC,” Official Journal of the European Union, 2006.
10. The European Parliament and the Council, “Directive 2005/32/EC,” Official Journal of the European Union, 2005.
11. EPTA Ltd., “Study for preparing the first Working Plan of the EcoDesign Directive,” Report No. ENTR/06/026, 2007.
12. Itoh, S., “Japan’s Energy Strategy and Development of Energy Cooperation in the Asia-Pacific,” ERINA Report, Vol. 77, pp. 35-48, 2007.
13. Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, “Energy Conservation Policy & Measures in Japan,” 2007.
14. Minami, N., “Japan’s Energy Conservation Initiatives: Highlighting the Energy Conservation Policy,” IEEJ Transactions on Electrical and Electronic Engineering, Vol. 3, No. 1, pp. 5-9, 2007.
15. Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, “Energy in Japan 2006,” pp. 7-12, 2006.
16. Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, “New National Energy Strategy,” 2006.
17. New Energy and Industrial Technology Development Organization, “Technology Strategy Map,” 2008.
18. Bladh, I., “Energy Efficiency in Manufacturing,” European Commission, 2009.
19. Draganescu, F., Gheorghe, M. and Doicin, C. V., “Models of Machine Tool Efficiency and Specific Consumed Energy,” Journal of Materials Processing Technology, Vol. 141, No. 1, pp. 9-15, 2003.
20. Bolliger, M., Gallestey, E., Crosley, G. and Kiener, M., “Energy Optimization in Cement Manufacturing,” ABB Review, Vol. 2, pp. 53-57, 2007.

21. Sutherland, J. W., Adler, D. P., Haapala, K. R. and Kumar, V., "A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production," CIRP Annals - Manufacturing Technology, Vol. 57, No. 1, pp. 5-8, 2008.

22. Dietmair, A. and Verl, A., "Energy Consumption Forecasting and Optimisation for Tool Machines," Modern Machinery Science Journal, pp. 62-67, 2009.

23. Herrmann, C. and Thiede, S., "Process Chain Simulation to Foster Energy Efficiency in Manufacturing," CIRP Journal of Manufacturing Science and Technology, Vol. 1, No. 4, pp. 221-229, 2009.

24. Wolters, W. T. M., Lambert, A. J. D. and Claus, J., "Sequencing problems in designing energy efficient production systems," International Journal of Production Economics, Vol. 41, No. 1-3, pp. 405-410, 1995.

25. David, J. L., "The Smart Grid in 2010 - Market Segments, Applications and Industry Players," GTM Research, pp. 10-45, 2009.

26. Anastasopoulos, M. P., Voulkidis, A. C., Vasilakos, A. V. and Cottis, P. G., "A secure network management protocol for SmartGrid BPL networks: Design, implementation and experimental results," Computer Communications, Vol. 31, No. 18, pp. 4333-4342, 2008.

27. Coll-Mayor, D., Paget, M. and Lightner, E., "Future intelligent power grid: Analysis of the vision in the European Union and the United States," Energy Policy, Vol. 35, No. 4, pp. 2453-2465, 2007.

28. Chassin, D. P. and Kiesling, L., "Decentralized Coordination through Digital Technology, Dynamic Pricing, and Customer-Driven Control: The GridWise Testbed Demonstration Project," The Electricity Journal, Vol. 21, No. 8, pp. 51-59, 2008.

29. Battaglini, A., Lilliestam, J., Haas, A. and Patt, A., "Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources," Journal of Cleaner Production, Vol. 17, No. 10, pp. 911-918, 2009.

30. Nair, N. K. C. and Zhang, L., "SmartGrid: Future networks for New Zealand power systems incorporating distributed generation," Energy Policy, Vol. 37, No. 9, pp. 3418-3427, 2009.

31. Kim, T. H., "Korea to Save Power Through Smart Grid," The Korea Times, 2009.

32. Chan, T., "Korea to create huge smart grid industry," Greentelecomlive, 2009.

33. Koizawa, K., "Smart Grid related R&D in NEDO," New Energy and Industrial Technology Development Organization, 2009.

34. Saha, A. K., Chowdhury, S., Chowdhury, S. P. and Crossley, P. A., "Microturbine Based Distributed Generator in Smart Grid Application," IET Digest, Vol. 2008, No. 12380, pp. 11-14, 2008.

35. Agafiotis, C. and Tsoutsos, T., "Energy saving technologies in the European ceramic sector: a systematic review," Applied Thermal Engineering, Vol. 21, No. 12, pp. 1231-1249, 2001.

36. Worrell, E., Faaij, A. P. C., Phylipsen, G. J. M. and Blok, K., "An approach for analysing the potential for material efficiency improvement," Resources, Conservation and Recycling, Vol. 13, No. 3, pp. 215-232, 1995.

37. Hekkert, M. P., Joosten, L. A. J., Worrell, E. and Turkenburg, W. C., "Reduction of CO_2 emissions by improved management of material and product use: the case of primary packaging," Resources, Conservation and Recycling, Vol. 29, No. 1, pp. 33-64, 2000.

38. Behrens, B. A., Suchmann, P. and Schott, A., "Warm forging: new forming sequence for the manufacturing of long flat pieces," Production Engineering, Vol. 2, No. 3, pp. 261-268, 2008.

39. European Commission, "EU energy research," 2008.

40. European Commission, "Energy Research in the 7th framework programme," 2007.

41. European Commission, "Work Programme 2010, Cooperation THEME 4-NMP," 2009.

42. AIAG FoF PPP, "Factories of the Future PPP - Draft Strategic Multi-annual Roadmap," 2009.

43. Zoz, H., Kaupp, G., Ren, H., Goepel, K. and Naimi-Jamal, M. R., "Recycling of EAF dust by semi-continuous high kinetic process," Metall, Vol. 59, No. 5, pp. 293-296, 2005.

44. European Commission, "SME FP6 Project Catalogue-A Collection of Co-operative and Collective Research Projects," p. 186, 2008.

45. Nodeszeloss, http://www.ucm.es/info/nodeszel/main.htm

46. RotoFlex, http://rotoflex-eu.org

47. Intelligent Manufacturing System, http://www.ims.org

48. IMS2020, http://www.ims2020.net

49. IMS2020-Supporting Global Research for 2020 Manufacturing Vision, http://ims2020net.wik.is

50. Energy Efficient Manufacturing, http://ims2020net.wik.is/Research_Topics_List/KAT_2

51. D'Addona, D., Teti, R. and Carbone, R., "Quick Response Manufacturing Approach for Lead Time Reduction in PCB Fabrication," IPROMS 2006, 2006.

52. Papagiannis, G., Dagoumas, A., Lettas, N. and Dokopoulos, P.,

"Economic and environmental impacts from the implementation of an intelligent demand side management system at the European level," Energy Policy, Vol. 36, No. 1, pp. 163-180, 2008.

53. Unger, N., Schneider, F. and Salhofer, S., "A review of ecodesign and environmental assessment tools and their appropriateness for electrical and electronic equipment," Progress in Industrial Ecology - An International Journal, Vol. 5, No. 1-2, pp. 13-29, 2008.

54. Campatelli, G., "Analysis of the environmental impact for a turning operation of AISI 1040 steel," IPROMS 2009, 2009.

55. Zhu, Z. and Mekid, S., "Energy harvesting for wireless sensor nodes: investigation of architectures and sources of energy," International Journal of Computer Aided Engineering and Technology, Vol. 1, No. 2, pp. 239-249, 2009.

56. Kimura, F., "An approach to configuring environmentally conscious manufacturing systems," J. of JSPE, Vol. 71, No. 8, pp. 941-945, 2005.

57. Ohashi, T. and Kawaguchi, T., "Environment-conscious plant and process for vehicle manufacturing," J. of JSPE, Vol. 71, No. 8, pp. 946-948, 2005.

58. Abe, H., "Environmental conscious production system of RICOH group," J. of JSPE, Vol. 71, No. 8, pp. 949-953, 2005.

59. Sekiguchi, T., "Trend and next development of cutting tool for eco-machining," J. of JSPE, Vol. 75, No. 1, pp. 123-125, 2009.

60. Motonishi, S., "Progress of PVD coated tools," J. of JSPE, Vol. 75, No. 1, pp. 70-71, 2009.

61. Matsubara, T., "Present state and problems of eco-machining technology," J. of JSPE, Vol. 68, No. 7, pp. 885-889, 2002.

62. Yokota, H., "Current MQL machining and its next development," J. of JSPE, Vol. 68, No. 7, pp. 903-906, 2002.

63. Nakamura, T., "On film on water fog metalworking fluid," J. of JSPE, Vol. 68, No. 7, pp. 899-902, 2002.

64. Ukai, H., "Dry cutting technology by nitrogen gas," J. of JSPE, Vol. 68, No. 7, pp. 890-894, 2002.

65. Mukai, R., "Trend to reducing technology of environment load in grinding machine," J. of JSPE, Vol. 68, No. 7, pp. 911-914, 2002.

66. Tadashi, M., "Development and trend of machine tools for MQL," Tool Engineer, Vol. 47, No. 4, pp. 44-49, 2003.

67. Koji, O., "Environment-conscious technology in machine tool maker," Tool Engineer, Vol. 52, No. 8, pp. 15-19, 2008.

68. Tadashi, M., "Environment-conscious machine tools and its use in automotive parts machining," Tool Engineer, Vol. 52, No. 8, pp. 20-25, 2008.

69. Hayashida, K., "Technical trend of steering system and grinding machine," J. of JSPE, Vol. 75, No. 1, pp. 136-137, 2009.

70. Kubo, A., "Machine elements," J. of JSPE, Vol. 75, No. 1, pp. 85-86, 2009.

71. Nakamura, S. and Miyaguchi, K., "Technical development of precision bearing and ball screw," J. of JSPE, Vol. 75, No. 1, pp. 121-122, 2009.

72. Kobayashi, T., "Progress of NTN's bearing technology in the past quarter century and its future perspective," J. of JSPE, Vol. 75, No. 1, pp. 130-131, 2009.

73. Kurita, T. and Hattori, M., "Development of new concept desk top size machine tool," Int. J. of Machine Tools & Manufacture, Vol. 45, No. 7-8, pp. 959-965, 2005.

74. Yoshiaki, K., "Present and future of TMC multifunctional machine," Tool Engineer, Vol. 47, No. 11, pp. 18-22, 2003.

75. Tsuneo, K., Toshihiro, Y., Akkinori, K. and Hideki, T., "TOPEMS optimal operation system for energy saving in manufacturing plants," Toshiba review, Vol. 62, No. 8, pp. 45-48, 2007.

76. Caterpillar Japan, "Global warming prevention by factory integrity," The Energy Conservation Center in Japan, Case Studies of Excellent Energy Saving, pp. 1-8, 2008.

77. Masao, D., "Energy saving in heavy machine manufacturing shop," Tool Engineer, Vol. 52, No. 8, pp. 10-14, 2008.

78. Keisuke, K., "A new point of time energy saving by low pressurization," Tool Engineer, Vol. 52, No. 8, pp. 26-28, 2008.

79. Aoki, I., "Precision fine blanking," J. of JSPE, Vol. 75, No. 1, pp. 56-57, 2009.

80. Worrell, E. and Galitsky, C., "Energy efficiency improvement and cost saving opportunities for cement making; An energy star® guide for energy and plant managers," Lawrence Berkeley National Laboratory, LBNL-54036-Revision, 2008.

81. Jahanmir, S., Ives, L. K., Ruff, A. W. and Peterson, M. B., "Ceramic Machining: Assessment of Current Practice and Research Needs in the United States 1992," NIST Special Publication, Vol. 834, Shipping list no.: 92-2331-M, 1992.

82. Bentzen, J., "Estimating the rebound effect in US manufacturing energy consumption," Energy Economics, Vol. 26, No. 1, pp. 123-134, 2004.

83. Djassemi, M., "A parametric programming technique for efficient CNC machining operations," Computers & Industrial Engineering, Vol. 35, No. 1-2, pp. 33-36, 1998.

84. Schmitz, T., Davies, M., Dutterer, B. and Ziegert, J., "The application of high-speed CNC machining to prototype production," International Journal of Machine Tools and

Manufacture, Vol. 41, No. 8, pp. 1209-1228, 2001.

85. Rakwal, D. and Bamberg, E., "Slicing, cleaning and kerf analysis of germanium wafers machined by wire electrical discharge machining," Journal of Materials Processing Technology, Vol. 209, No. 8, pp. 3740-3751, 2009.

86. Miller, S. F., Shih, A. J. and Qu, J., "Investigation of the spark cycle on material removal rate in wire electrical discharge machining of advanced materials," International Journal of Machine Tools & Manufacture, Vol. 44, No. 4, pp. 391-400, 2004.

87. Fox-Rabinovich, G. S., Yamomoto, K., Veldhuis, S. C., Kovalev, A. I. and Dosbaeva, G. K., "Tribological adaptability of TiAlCrN PVD coatings under high performance dry machining conditions," Surface & Coatings Technology, Vol. 200, No. 5-6, pp. 1804-1813, 2005.

88. Kovacevic, R., Cherukuthota, C. and Mazurkiewicz, M., "High pressure waterjet cooling/lubrication to improve machining efficiency in milling," International Journal of Machine Tools & Manufacture, Vol. 35, No. 10, pp. 1459-1473, 1995.

89. Calatoru, V. D., Balazinski, M., Mayer, J. R. R., Paris, H. and L'Espérance, G., "Diffusion wear mechanism during high-speed machining of 7475-T7351 aluminium alloy with carbide end mills," Wear, Vol. 265, No. 11-12, pp. 1793-1800, 2008.

90. Anderson, M., Patwa, R. and Shin, Y. C., "Laser-assisted machining of Inconel 718 with an economic analysis," International Journal of Machine Tools & Manufacture, Vol. 46, No. 14, pp. 1879-1891, 2006.

91. Draganescu, F., Gheorghe, M. and Doicin, C. V., "Models of machine tool efficiency and specific consumed energy," Journal of Materials Processing Technology, Vol. 141, No. 1, pp. 9-15, 2003.

92. Evans, L. B., "Saving Energy in Manufacturing with Smart Technology," World Energy, Vol. 6, No. 2, pp. 112-118, 2003.

93. Marksberry, P. W., "Micro-flood (MF) technology for sustainable manufacturing operations that are coolant less and occupationally friendly," Journal of Cleaner Production, Vol. 15, No. 10, pp. 958-971, 2007.

94. Weinert, K., Inasaki, I., Sutherland, J. W. and Wakabayashi, T., "Dry Machining and Minimum Quantity Lubrication," CIRP Annals - Manufacturing Technology, Vol. 53, No. 2, pp. 511-537, 2004.

95. Dasch, J. M., Ang, C. C., Wong, C. A., Waldo, R. A., Chester, D., Cheng, Y. T., Powell, B. R., Weiner, A. M. and Konca, E., "The effect of free-machining elements on dry machining of B319 aluminum alloy," Journal of Materials Processing Technology, Vol. 209, No. 10, pp. 4638-4644, 2009.

96. Williams, J. and Shu, L. H., "Analysis of Remanufacturer Waste Streams Across Product Sectors," CIRP Annals - Manufacturing Technology, Vol. 50, No. 1, pp. 101-104, 2001.

97. Adler, D. P., Kumar, V., Ludewig, P. A. and Sutherland, J. W., "Comparing Energy and Other Measures of Environmental Performance in the Original Manufacturing and Remanufacturing of Engine Components," Proc. of the 2007 ASME International Manufacturing Science and Engineering Conference, pp. 1-10, 2007.

98. Amezquita, T., Hammond, R. and Bras, R., "Characterizing the Remanufacturability of Engineering Systems," Proc. of 1995 ASME Adv. in Des. Automation Conference, pp. 271-278, 1995.

99. Lund, R. T. and Hauser, W., "The Remanufacturing Industry: Anatomy of a Giant," Department of Manufacturing Engineering, Boston University, 2003.

100. Bollinger, L., Frenkel, R., Grand, R., Kutta, R., Lund, R. and Stanovsky, C., "Remanufacturing Survey Findings," Center for Policy Alternatives, MIT, 1981.

101. Larsen, H. and Petersen, L. S., "Future options for energy technology," Riso Energy Report 6, Riso National Lab. Technical University of Denmark, 2007.

102. The NEED Project, "Intermediate Energy Infobook," 2009.

103. Kan, Y., Shida, R., Takahashi, J. and Uzawa, K., "Energy saving effect of light weight electric vehicle using CFRP on transportation sector," 10^{th} Japan International SAMPE Symposium & Exhibition, 2009.

104. New Energy and Industrial Technology Development Organization, "Japanese Technologies for energy savings/ GHG Emissions Reduction," 2008.

105. Rob, G. R., "Future transportation with smart grids & sustainable energy," Journal of Systemics, Cybernetics and Informatics, Vol. 7, No. 5, pp. 4-8, 2009.

106. Andrews, C. J. and Krogmann, U., "Technology diffusion and energy intensity in US commercial buildings," Energy Policy, Vol. 27, No. 2, pp. 541-553, 2009.

107. Sanches, M. C., Brown, R. E., Webber, C. and Homan G. K., "Savings estimates for the United States Environmental Protection Agency's Energy Star voluntary product labeling program," Energy Policy, Vol. 36, No. 6, pp. 2098-2108, 2008.

108. Barrett, M., Lowe, R., Oreszczyn, T. and Steadman P., "How to support growth with less energy," Energy Policy, Vol. 36, No. 12, pp. 4592-4599, 2008.

109. Jung, J.-W., Ko, S.-H., Jeong, Y.-H., Min, B.-K. and Lee, S. J., "Real-time Gap Control for Micro-EDM: Application in a Microfactory," IJPEM, Vol. 9, No. 1, pp. 3-6, 2008.

110. Okazaki, Y., Mishima, N. and Ashida, K., "Microfactory -

Concept, history, and developments," Journal of Manufacturing Science and Engineering, Vol. 126, No. 4, pp. 837-844, 2004.

111. Mishima, N., Kondo, S. and Masui, K., "A Study on Efficiency Analysis of Micro Manufacturing Systems," Proc. of the 2007 IEEE, International Conference on Mechatronics and Automation, pp. 51-56, 2007.

112. Kurita, T. and Hattori, M., "Development of new-concept desk top size machine tool," International Journal of Machine Tools & Manufacture, Vol. 45, No. 7-8, pp. 959-965, 2005.

113. Nakano, S., Ashida, K., Park, J. and Akedo, J., "On demand manufacturing system ~a solution of ecological MEMS factory," 6th International Workshop on Microfactories, 2008.

114. Landymore, K. "Electrical Energy Reduction in Refrigeration and Air Conditioning," Smartcool Systems Inc., 2006.

115. Energy Information Administration, "International Energy Outlook 2009," U.S. Department of Energy, 2009.

116. International Energy Agency, "Tracking Industrial Energy Efficiency and CO2 Emissions," 2007.

117. International Energy Agency, "CO2 Emissions from Fuel Combustion (2003 Edition)," 2004.

118. Energy Information Administration, "International Energy Outlook 2006," U.S. Department of Energy, 2006.

119. Energy Information Administration, "International Energy Outlook 2007," U.S. Department of Energy, 2007.

120. Energy Information Administration, "International Energy Outlook 2008," U.S. Department of Energy, 2008.

121. Narita, H. and Fujimoto, H., "Analysis of Environmental Impact due to Machine Tool Operation," Int. J. of Automation Technology, Vol. 3, No.1, pp. 49-55, 2009.

122. IPCC 3rd Assessment Report - Climate Change 2001, "Chapter 6 - Radiative Forcing of Climate Change," Intergovernmental Panel on Climate Change, 2001.

123. Korea Energy Economics Institute, "Trends in the greenhouse gas emissions," 2006.

124. Energy Information Administration, "Emissions of Greenhouse Gases in the United States 2007," U.S. Department of Energy, 2008.

125. Stachowiak, G. W. and Batchelor, A. W., "Engineering tribology: 3rd ed.," Butterworth-Heinemann, pp. 709-710, 2005.

126. Korea Energy Economics Institute, "2008 Energy Consumption Survey," Korea Ministry of Knowledge Economy, 2009.

127. Energy Information Administration, "2006 Consumption of Energy for All Purposes (First Use) By Manufacturing Industry & Region," U.S. Department of Energy, 2009.

128. Industrial Consumption of Energy Survey, "Summary Report of Energy Use in the Canadian Manufacturing Sector 1995-2005," Canada Office of Energy Efficiency, 2008.

129. Canada Office of Energy Efficiency, "Energy Use Data Handbook Tables (Industrial sector)," Natural resources Canada, 2009.

130. Energy Information Administration, "International Energy Annual 2006," U.S. Department of Energy, 2008.

131. Energy Conservation Center in Japan, "Japan Energy Conservation Handbook 2005/2006," 2006.

132. MacLeay, I., Harris, K. and Michaels, C., "Digest of United Kingdom Energy Statistics 2007," Department for Business Enterprise and Regulatory Reform, 2007.

133. Norway Statistics, "Industrial energy use, temporary data, 2008 - Powerful increase in energy costs," 2009.

134. Welch, D., "Manufacturing Energy Use Survey: Year ended March 2006," Statistics New Zealand, 2007.

135. Dang, H., Tamayo, J. and Wilkinson, D., "New Zealand Energy in Brief," New Zealand Ministry of Economic Development, 2007.

136. Energy Information Administration, "Annual Energy Outlook 2008 With Projections to 2030," U.S. Department of Energy, 2008.

137. Briefing Note and referenced information, "BNXS01: Carbon Dioxide Emission Factors for UK Energy Use," 2009.

138. PointCarbon, http://www.pointcarbon.com.

139. Hoekstra, R. and van der Bergh, H., "Comparing structural and index decomposition analysis," Energy Economics, Vol. 25, No. 1, pp. 39-64, 2003.

140. Ang, B. W. and Liu, N., "Energy decomposition analysis: IEA model versus other methods," Energy Policy, Vol. 35, No. 3, pp. 1426-1432, 2007.

141. Ang, B. W. and Liu, N., "Handling zero values in the logarithmic mean Divisia index decomposition approach," Energy Policy, Vol. 35, No. 1, pp. 238-246, 2007.

142. Ang, B. W. and Zhang, F. Q., "A survey of index decomposition analysis in energy and environmental studies," Energy, Vol. 25, No. 12, pp. 1149-1176, 2000.

143. Liu, F. L. and Ang, B. W., "Eight methods for decomposing the aggregate energy intensity of industry," Applied Energy, Vol. 76, No. 1-3, pp. 15-23, 2003.

144. Boyd, G. A. and Roop, J. M., "A note on the Fisher ideal index decomposition for structural change in energy intensity," The

Energy Journal, Vol. 25, No. 1, pp. 87-101, 2004.

145. Ang, B. W., Liu, F. L. and Chung, H. S., “A generalized Fisher index approach to energy decomposition analysis,” Energy Economics, Vol. 26, No. 5, pp. 757-763, 2004.

146. Boer, P., “Generalized Fisher index or Siegel–Shapley decomposition?,” Energy Economics, Vol. 31, No. 5, pp. 810-814, 2009.

147. Lenzen, M., “Decomposition analysis and the mean-rate-of-change index,” Applied Energy, Vol. 83, No. 3, pp. 185-198, 2006.

148. Chung, H. S. and Lee, H. C., “A residual-free decomposition of the sources of carbon-dioxide emissions: a case of the Korean industries,” Energy, Vol. 26, No. 1, pp. 15-30, 2001.

149. Lescaroux, F., “Decomposition of US manufacturing energy intensity and elasticities of components with respect to energy prices,” Energy Economics, Vol. 30, No. 3, pp. 1068-1080, 2008.

150. Unander, F., “Decomposition of manufacturing energy-use in IEA countries, How do recent developments compare with historical long-term trends?,” Applied Energy, Vol. 84, No. 7-8, pp. 771-780, 2007.

151. Weber, C. L., “Measuring structural change and energy use: Decomposition of the US economy from 1997 to 2002,” Energy Policy, Vol. 37, No. 4, pp. 1561-1570, 2009.

152. Sun, J., “Changes in energy consumption and energy intensity: a complete decomposition model,” Energy Economics, Vol. 20, No. 1, pp. 85-100, 1998.

153. Diakoulaki, D. and Mandaraka, M., “Decomposition analysis for assessing the progress in decoupling industrial growth from CO2 emissions in the EU manufacturing sector,” Energy Economics, Vol. 29, No. 4, pp. 636-664, 2007.

154. Papagiannaki, K. and Diakoulaki, D., “Decomposition analysis of CO_2 emissions from passenger cars: The cases of Greece and Denmark,” Energy Policy, Vol. 37, No. 8, pp. 3259-3267, 2009.

155. Greening, L. A., Ting, M. and Davis, W. B., “Decomposition of aggregate carbon intensity for freight: trends from 10 OECD countries for the period 1971-1993,” Energy Economics, Vol. 21, No. 4, pp. 331-361, 1999.

156. Schipper, L., Scholl, L. and Price, L., “Energy use and carbon emissions from freight in 10 industrialised countries: an analysis of trends from 1973 to 1992,” Transportation Research Part D: Transport and Environment, Vol. 2, No. 1, pp. 57-76, 1997.

157. Scholl, L., Schipper, L. and Kiang, N., “CO_2 emissions from passenger transport: a comparison of international trends from 1973 to 1992,” Energy Policy, Vol. 24, No. 1, pp. 17-30, 1996.

158. Schipper, L., Steiner, R., Duerr, P., An, F. and Strøm, S., “Energy use in passenger transport in OECD countries: changes since 1970,” Transportation, Vol. 19, No. 1, pp. 25-42, 1992.

159. Kwon, T.-H., “Decomposition of factors determining the trend of CO_2 emissions from car travel in Great Britain (1970-2000),” Ecological Economics, Vol. 53, No. 2, pp. 261-275, 2005.