Title
Potentials and policy implications of energy and material efficiency improvement

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Potentials and Policy Implications of Energy and Material Efficiency Improvement

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Contents

Foreword

There is a growing awareness and appreciation of the importance of improved efficiency of energy and material use. Reducing energy and material use per unit of economic output will not only lead to economic savings but also reduce adverse environmental impacts. Enhancing eco-efficiency greatly contributes to sustainable development. Indeed, economic potentials for energy and material efficiency improvement in the developing countries and countries in economic transition are at least as large as those in the industrialized countries.

The Committee on New and Renewable Sources of Energy and on Energy for Development decided to consider the issue of efficiency improvements in energy and materials at its second session in February 1996 in New York. Consequently, the Division for Sustainable Development of the Department for Policy Coordination and Sustainable Development, commissioned the services of Ernst Worrell, Richard van den Broek and Kornelis Blok of the Department of Science, Technology and Society, Utrecht University, The Netherlands, as well as those of Mark Levine, Lynn Price and Nathan Martin of the Energy and Analysis Programme, Lawrence Berkeley National Laboratory, USA, to prepare a status report on the subject. A shorter version of the present report (E/C.13/1996/5) was presented for consideration by the Committee and was very well received. The Committee, therefore, recommended that the full report be distributed for wider dissemination.

The funding for the report was provided by the Ministry of Economic Affairs, The Netherlands, to which I should like to express our appreciation.

The present report is an example of the continuing effort by the United Nations and by the Department of Policy Coordination and Sustainable Development to obtain and distribute widely information on sustainable development issues of importance and concern to the international community.

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1. Introduction

1.1 The Need for a Low Energy Path

There is a growing awareness of serious problems associated with the provision of sufficient energy to meet human needs and to fuel economic growth worldwide. Current energy production and usage patterns rely heavily on combustion of fossil fuels, a key factor in the unprecedented increase in carbon dioxide (CO_2) concentrations in the earth's atmosphere that contribute to global warming [IPCC,1996]. International policy documents like Agenda 21 and the Framework Convention on Climate Change (FCCC) underline the international recognition of the problem of climate change in particular, as well as other environmental problems associated with the use of energy. Some key environmental problems are regional (acidification of soil and water), local (smog, urban air quality, solid wastes, effluents and thermal pollution) or indoor air pollution.

In many areas of the world, particularly the developing country mega-cities, the health and environmental effects of such patterns of energy use are even more extreme, as technologies and policies for abating pollution and producing cleaner energy are not always available or implemented. Given current patterns of population and economic growth in the developing world, these health and environmental problems will continue to worsen [UNEP/WHO,1992].

In 1987, the World Commission on Environment and Development (WCED) concluded that the best route to sustainable development of the energy system is a "*low energy path*", which means that nations should take the opportunities "*to produce the same levels of energy services with as little as half the primary energy currently consumed*" [WCED,1987]. The improvement of energy efficiency, or the more rational use of energy, is generally viewed as the most important option in the near term to reduce greenhouse gas emissions and to reduce the negative impacts of the use of energy and/or fossil fuels. Energy efficiency is defined as *decreasing the use of energy per unit activity without substantially affecting the level of these activities*. Reducing energy consumption has other benefits as well, e.g. increased employment, improved balance of imports and exports, and increased security of energy supply. Reduced energy intensity will also make it much easier to adopt environmentally-advantageous energy supply (e.g. non-fossil and renewable energy sources). These benefits are especially of interest to energy-importing developing nations that shoulder a heavy burden to support growing energy demand [OTA,1992a].

1.2 Energy and Material Efficiency

The main factors affecting energy growth in an economy include the energy consumed per unit of economic activity, the size and structure of the economy (depending on consumption patterns and stage of development), and the rate of population growth. If an economy is growing rapidly or population growth is high, then energy demand will rise commensurately, assuming there is no change in the level of energy consumption per unit of economic output. This is the case with many developing countries, in which economic growth and the expansion of population are rapidly overtaking efficiency improvements within the economy. The amount of energy consumed per unit of economic growth is affected by how efficiently energy is used to provide energy services in an economy. Shifts in the structure of the economy, in which the overall level of energy services required to produce additional economic output changes, also influence energy use. All else being equal, reducing economic or population growth will also lead to reductions in energy demand. Reducing population growth will, over the long term, have a profound effect on energy demand. However, most of the impacts of changes in policies affecting population growth are beyond the time horizon for this study.

In the near and medium term, the most effective and feasible policies for restraining energy growth involve improving the efficient use of energy in all sectors (agriculture, industry, buildings, and transportation) and encouraging the shift to a less energy-intensive economic and industrial structure. Of all economic activities, the industrial sector consumes 43% of world energy, of which the largest part is for the production of basic materials such as metals, chemicals, pulp and paper, and non-metallic minerals (building materials). Therefore improving industrial energy efficiency will continue to play a key role in a sustainable future. At the same time, some of the fastest growth in energy use has taken place in the transportation sector, where the energy use for personal mobility and for freight have both grown at faster than average world energy levels. Increased mechanisation in agriculture leads also to an increased energy demand, and to increased use of commercial fuels instead of traditional practices in developing countries. Finally, increasing electrification and demand for energy services in buildings such as lighting, heating, computers and other electronic equipment, is also substantially driving up primary energy use.

In the industrial sector, the consumption of energy is also dependent on how efficiently basic materials are used in the creation of intermediate and final products (material efficiency). The use of less material to produce the same or better product helps to encourage the shift to a less energy-intensive economic or industrial structure. By analogy to energy efficiency improvement, material efficiency improvement is described as *reducing the consumption of primary materials without substantially affecting the service or function*, or - in a broader definition- *without affecting the level of human activities qualitatively*. Figure 1.1 gives a strongly simplified schematic representation of the energy and materials system within the economic and environmental systems. Energy efficiency improvement is represented as a reduction of the horizontal streams through the economic system. Material efficiency improvement aims at the reduction of the vertical streams reducing leakages, closing of chains or reducing the size of the (primary) material influx through an economic sector (efficiency improvement). Reducing the stream will affect the energy needs (in the horizontal direction).

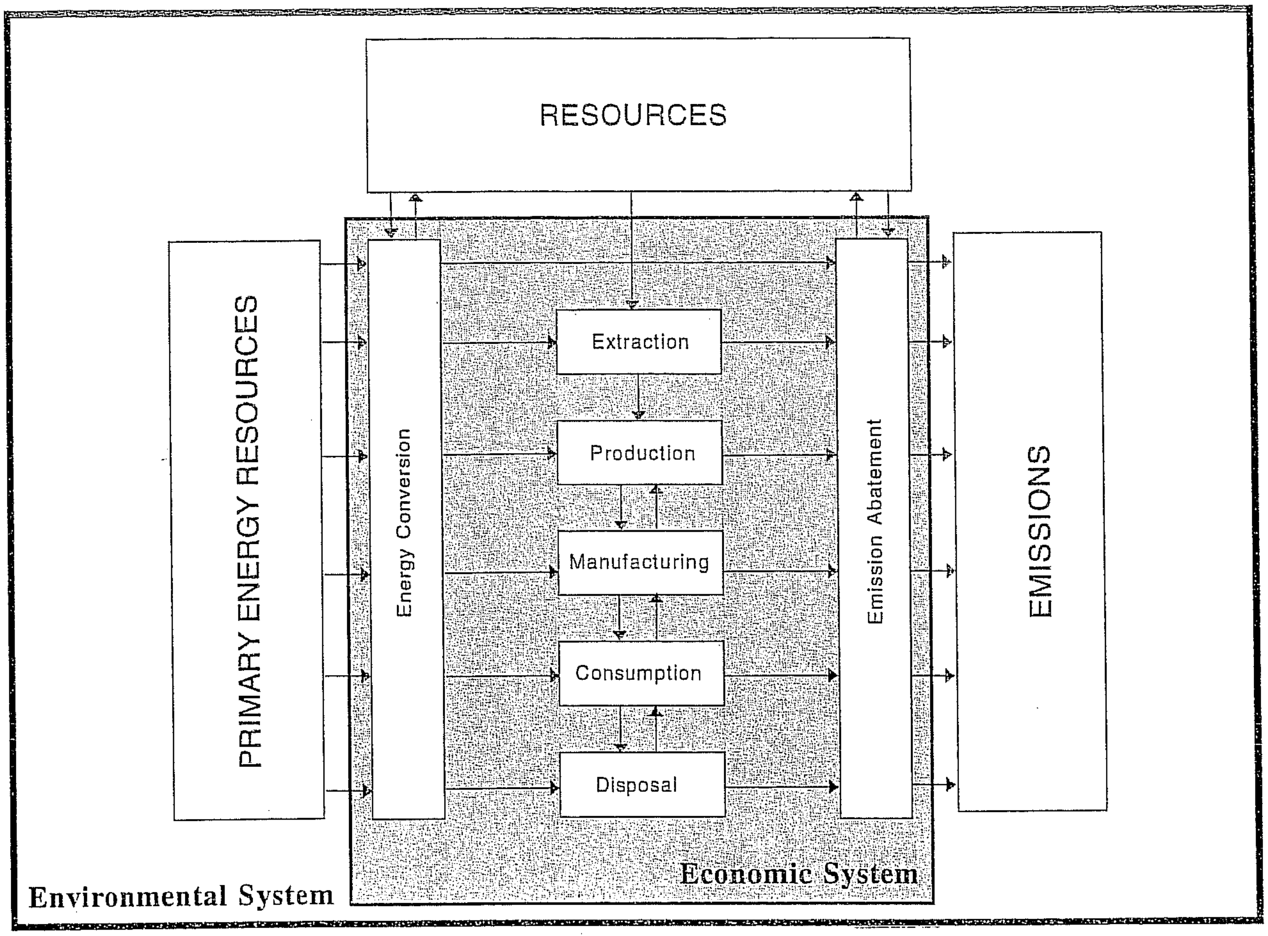

Figure 1.1 Simplified schematic representation of material and energy streams in the economic system. Vertical streams represent material streams. Horizontal streams represent energy flows. For purposes of simplification many interactions between streams and economic sectors are not depicted.

1.3 Focus of this Study

This study focuses on determination of the potentials for energy and material efficiency improvement and subsequent policy implications. The study will report to the UN Committee on New and Renewable Sources of Energy and on Energy for Development (UNCNRSEED). The report is the product of an international team of researchers coordinated by the Department of Science, Technology & Society of Utrecht University, The Netherlands. The team consisted of researchers from the Energy Analysis Program of Lawrence Berkeley National Laboratory, USA, and Utrecht University. The report was reviewed by international experts from Kenya, and the USA.

The study discusses trends in energy use in four major economic sectors - agriculture, industry, buildings, and transport - and explores the potentials for energy efficiency improvement. The countries of the world are divided into three aggregate regions: Industrialized (OECD) countries (ICs), the economies in transition in Eastern Europe and the former Soviet Union (EITs), and developing countries (DCs). For this assessment we developed three scenarios: *business-as-usual, state-of-the-art*, and *ecologically driven/advanced technology*. The business-as-usual scenario assumes the continued use of current technologies and continuing efficiency improvements caused mainly by stock turn over and shifts to industrial activities of lower energy intensity (i.e. so-called structural change). The state-of-the-art scenario assumes the replacement of existing stock with the current most efficient technologies available. The ecologically driven/advanced technology assumes a more rapid uptake of current state-of-the-art technologies and adoption of some advanced technologies, which are now demonstrated or under development. The potentials for material efficiency improvement are analyzed in chapter three, considering consumption patterns, trends and reduction estimates. The extent to which energy and material efficiency potentials (as determined in the three scenarios) are met will depend on the successful implementation of policies within countries, as well as suitable frameworks in an international context. A wide range of instruments have been applied within the context of energy policy, under various constraints and considerations (e.g. target groups, economics, legal systems, etc.). Chapter four assesses the implementation barriers and the major policy instruments. An in-depth analysis of effectiveness is presented, with emphasis on developing countries (using mainly studies from industrialized countries). We conclude with policy recommendations and conclusions that can be drawn from our assessment.

In this study all energy values are represented in SI-units, e.g. Joules. Energy consumption is presented in primary values to account for the linkage between end-use activities and the primary energy demand that such activities generate. Losses in the delivery or transformation of energy, particularly for electricity, can be significant. Unless otherwise noted, all fuels have been converted to standard (primary) energy equivalent units in order to allow for ease of comparability.[1]

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1 Converting the end-use of energy into its primary equivalent is difficult since each country has a different fuel mix. We have assigned an average approximation for the conversion of electricity. We use a conversion factor for primary energy into electricity of 3.1 for industrialized countries and 3.5 for non-ICs. Such an approximation inaccurately reflects the situation of many individual countries. Also, the assignment of one conversion factor for the whole time period of the study does not capture improvements of generation efficiency. In future analyses, we intend to modify this assumption, and include the effects of efficiency improvements in electricity generation.

2. Assessment of Energy Efficiency Improvement

In this chapter we assess the potentials for energy efficiency improvement in four sectors: agriculture, industry, buildings and transport. For each sector we present the trends in energy use over the past decades, followed by a discussion of the potentials to improve energy efficiency in the period from 1990 to 2020. Each sectoral discussion concludes with three scenarios for implementation of efficiency improvement, disaggregated for the three regions.

2.1 Agriculture

2.1.1 Introduction

Energy consumption in agriculture is divided into direct (on-farm) and indirect (for e.g. fertilizers, pesticides) energy use. Direct energy consumption by agriculture comprised about 3% of total world energy consumption in 1990 [WEC,1995a]. For the regions DC, EITs and ICs this was 5, 4 and 2% respectively. Pimentel and Hall (1984) estimate that only 35% of the total commercial energy consumed in US food production is consumed on the farm. The rest is for food processing, packaging, storage, transport and preparation. Direct commercial energy consumption varies significantly depending on agricultural practice and crop, as can be seen in table 2.1. Yields depend on many factors, including climate conditions and nutrient inputs. In traditional agriculture, direct energy consumption can be solely noncommercial. Table 2.2 compares direct and indirect energy consumption (including important sources such as animal and human labour) of the relatively energy-intensive crop rice for some different types of agriculture. In this report fertilizer production and potential energy savings are discussed in section 2.2 and chapter 3.

Table 2.1. Direct energy consumption in different agricultural types with different crops.

	Direct energy consumption per hectare [GJ/ha]			Direct energy consumption per tonne [GJ/wet tonne]	
	USA[1]	China[1]	India[2]	USA[1]	China[1]
maize	6.16	2.00	1.23	1.2	0.4
rice	28.21	9.83	2.22	4.3	1.2
wheat	4.84	2.12	3.92	2.4	1.1
sorghum	49.57	0.41	0.11	11.9	0.1

1. Data are from different individual case studies in China and USA between 1977 and 1981 [Pimentel,1984].
2. Data are average values over different case studies in India in 1986 and 1987 [Dhawan et al.,1993]. Data on yields were not available.

Total direct energy consumption is estimated as 32% of total world agricultural commercial energy (including indirect energy inputs) consumption by Stout (1989) and as 34% by Pimentel and Hall [1984]. Here we focus at direct on-farm consumption of commercial energy. In a strategy towards energy efficiency improvement in agriculture, however, both direct and indirect energy have to be included in order to find optimized solutions. For a discussion of social issues we refer to [UNCNRSEED,1995].

Time series of direct energy consumption in world agriculture are only available as aggregated figures per country. Although disaggregation into different fuels is given in major energy statistics (e.g UN or IEA), disaggregation into commodities or operations is not present. On the other hand, in the more disaggregated agricultural statistics of the FAO, direct energy inputs are not included. Figure 2.1 shows estimates of agricultural energy consumption by region, based on IEA and British Petroleum statistics [WEC,1995a]. The main trend that can be seen from figure 2.1 is a slow growth in energy consumption in industrialized countries (2.1%/year average between 1980 and 1992), a faster growth in developing countries (4.5%/year between 1980 and 1992), with economies in transition at 0.8%/year. The energy consumption in EITs decreased 7.0%/year between 1990 and 1992 as a result of a sharply decreasing agricultural production. The statistical data is distorted by different definitions of the agricultural sector per country.[2] Bowers [1992] states that as the degree of mechanization increases, energy use increases per unit of product.

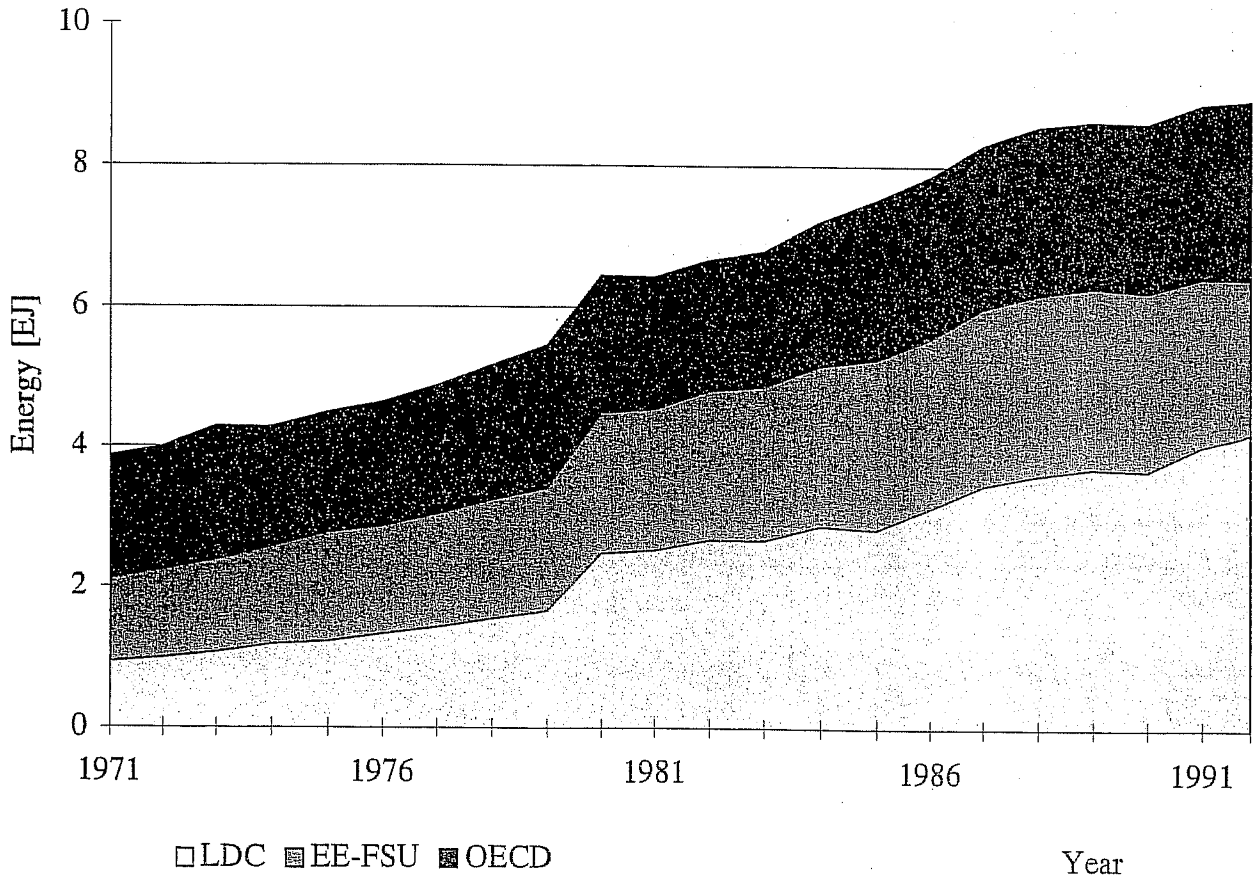

Figure 2.1 Global primary energy consumption in agriculture by region 1971-1992.

[2] For example: According to the IEA statistics, Indian agricultural energy consumption almost completely consists of electricity, which is very unlikely and contradictory to other Indian surveys [Dhawan et al.,1993].

Table 2.2. Total on-farm energy consumption in rice production for different agricultural practices.

	Energy consumption per hectare [GJ/ha][1]			
	USA	China	India	Philippines
Noncommercial	0.1	12.9	4.9	3.5
Fuel	13.1	3.5	0.8	11.1
Irrigation	8.9	4.9	1.4	2.8
Drying	5.8	0.0	0.0	0.0
Other electricity	0.4	1.5	0.0	0.0
Total direct commercial	28.2	9.8	2.2	13.9
Fertilizers	9.0	10.8	4.5	7.4
Pesticides / herbicides	1.7	1.1	0.2	1.8
Seeds	3.0	2.0	1.3	3.2
Production of machinery	3.1	1.5	0.1	0.7
Total indirect commercial	16.5	15.4	5.6	13.1
Total commercial	45.1	25.2	7.9	27.0
Yield [wet tonne/ha]	6.5	8.1	n.a.	7.4
Total commercial energy [GJ/wet tonne]	6.9	3.1	n.a.	3.7

1. India is derived from Dhawan et al. [1993], others from Pimentel [1984]. Philippines is double harvesting.

Combining the data from Figure 2.1 with data on amount of arable land and production,[3] we can estimate direct energy consumption per hectare and per unit of production. The latter is shown in Figure 2.2. Direct energy consumption per hectare of arable land in world agriculture increased 3.3%/year on average between 1980 and 1990, and per unit product only 1.1%/year. The difference can be explained by the increase in productivity per hectare. For developing countries these figures were 4.2 and 1.4%/year respectively.

In line with Faidley (1992) and Stout (1989), it is possible to estimate time series of direct agricultural energy consumption for tractors and irrigation. This is based on the number of irrigated hectares and the number of tractors in the different regions [FAO,1995; WRI,1992].[4]

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3 Production is estimated by the total production of cereals, for they account for roughly 50% of global consumption of food energy. This same argument is used in the World Bank's "Resources and Global Food Prospects" to focus on cereals [Crosson and Anderson,1992].

4 Assumptions are made according to FAO estimations [Stout,1989]. Annual fuel consumption per tractor (GJ): 215 (North America), 151 (other ICs), 172 (EITs) and 129 (DCs); annual fuel consumption of irrigation equipment [GJ/ha] : 6.9 (ICs + EITs), 8.6 (Africa) and 7.7 (other DCs). Share of hectares of pure gravity irrigation in total hectares of irrigated land : 20% (ICs), 20% (EITs) and 50% (DCs) [Vermeiren,1995].

Tractors are by far the greatest consumers of fuel in field operations, accounting for 90-95% of the fuel used [Bowers,1992]. Energy consumption in field operations is affected by many factors, including weather, soil type, depth of tillage operations, field size, speed, degree of mechanization (manpower, animal power and mechanical power) and management ability. Mechanization is done for the purpose of increased labour productivity, improved quality of work and to overcome time constraints or critical operations (e.g. land clearing). It may improve yields through better land preparation, more precise placement of seed and fertilizer and more efficient harvesting [Stout,1989]. The degree of mechanization is determined by the relative costs for capital, energy and labour. In North America, tractors are used for nearly all crop production operations, in developing countries they are often only used for tillage and transportation [Stout,1989].

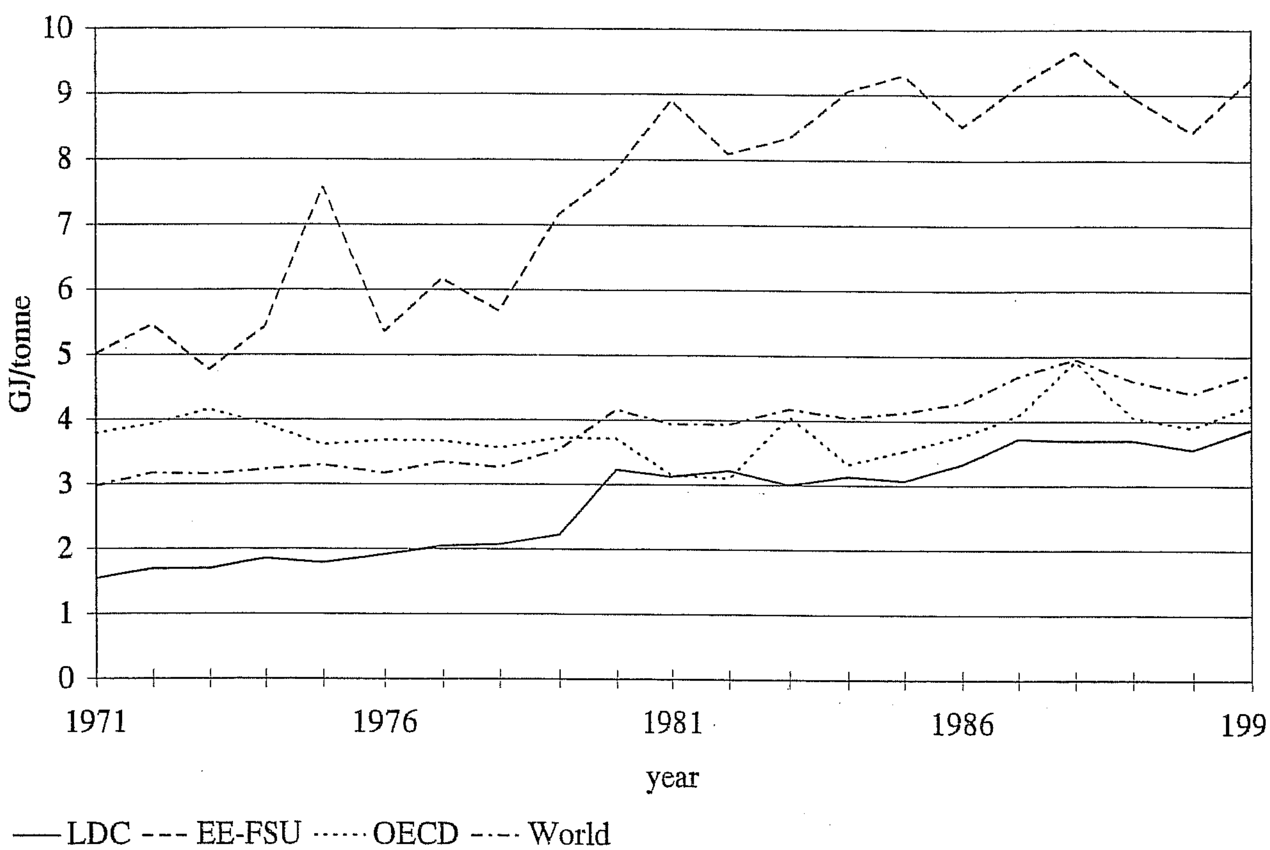

Figure 2.2. Development of agricultural energy consumption per tonne of cereals, by region.

It was estimated that about 15 % of the world's crop land is irrigated and that this area produces about 30% of the world's food [Sloggett,1992]. We can distinguish between systems powered by gravity and systems in which water has to be lifted by pumps over a certain height. We will focus at the latter type, because the gravity powered systems hardly use any direct commercial energy.

Other direct on-farm commercial energy input consists mainly of energy for drying and direct energy for animal production (accounting for 11 and 16% respectively of the total direct energy input in agriculture in the USA in 1976 [Smil,1992]) and direct energy for horticulture, such as heating, cooling, ventilation and lighting.

2.1.2 Efficiency improvement in agricultural energy consumption

Potential energy savings can be found through changes in the use and design of tractors, reduced tillage, and improvements in irrigation, drying, livestock production and horticulture. Renewable energy sources can also contribute to savings in fossil energy used in agriculture. Examples are solar and wind energy and energy from biomass residues or products from energy cropping for heat and power production, wind as direct source for irrigation and solar energy as direct source for drying. Because the focus in this report is on energy efficiency, we will not consider these options here. Potential energy savings in agriculture are summarized in table 2.3.

A range for the specific fuel consumption between 2.2 and 2.6 kWh/liter is common for modern tractors [Stout,1989]. The overall efficiency of tractors is the product of engine efficiency, drive train efficiency (transmission losses) and traction efficiency [Stout and McKiernan,1992]. However, the most important factor determining the fuel use of the tractor is the driving behaviour [Bergen and Biewinga,1992]. On all these items fuel saving potentials can be found in literature (see table 2.3). Driving behaviour and gear selection are very important, due to the wide variety of loads. The average power level of tractors is approximately 55-60% of their maximum load [Bowers,1992], with 30-50% of rated power being a frequently applied power level [Stout and McKiernan,1992]. Engine efficiency is the highest with the highest load factor, which under light load conditions may be achieved by shifting to a higher transmission gear and operating at reduced engine speed. Other measures of efficient tractor use include proper tire pressures, use of additional weights to optimize slip, combining operations, use machinery with maximum working width, avoiding unnecessary running of the engine, proper adjustment of crankshaft, use of sharp and properly adjusted ploughs, and proper capacity tractor [Bergen and Biewinga,1992]. Because of inherent limitations for transmitting usable power to a field machine through wheels or tracks, cable towing systems could be a suitable alternative for some application in the future [Stout and McKiernan,1992].

Table 2.3. Technical potential for energy efficiency improvement in agriculture. The estimated improvement potentials are expressed as function of energy consumption for the category.

Measure	Potential	Region
Tractors		
Using higher gears under light load conditions	17-28%[1]	U.S.A.
Using higher gears under light load conditions	18%[16]	Canada
Variety of measures that concern rational use of tractors	25%[2]	The Netherlands
Appropriate monitor and information feedback	15-20%[3]	U.S.A.
Automatic control of gears	5-12%[4]	U.S.A.
Future developments of diesel engines	12-38%[5]	U.S.A.

Measure	Potential	Region
Future developments of diesel engines	14%[2]	The Netherlands
Improved hydrostatic transmission	7.5%[6]	The Netherlands
Reduced friction in the machinery	10%[2]	The Netherlands
Use of cable towing systems	50%[7]	U.S.A.
Reduced tillage	70-80%[8]	E.U.
	38-69%[9]	Germany
	34%[10]	U.S.A.
	43-78%[11]	U.S.A.
Eliminating tillage during summer fallow	4%[16]	Canada
Irrigation		
Low energy precision application system	43-86%[12]	U.S.A.
Good design and installation of pumps	27-33%[12]	U.S.A.
Retrofitting existing pump sets	23-29%[13]	India
Upgrading of inefficient agricultural pumpsets	30-50%[14]	Africa
Drying		
Combined high/low instead of high temperature drying	20%[15]	U.S.A.
Heat recovery systems for exhaust gas	10-18%[15]	U.S.A.
Optimised instead of continuous fan operation	20-55%[15]	U.S.A.
Livestock production		
Improved insulation	15%[2]	The Netherlands
More efficient cooling	60%[16]	The Netherlands
Hot water production	60%[16]	The Netherlands
Horticulture		
Computer climate control	10%[6]	The Netherlands
Insulation screens	20%[2]	The Netherlands
Variable glazing systems for additional insulation	40%[17]	United Kingdom
Soil heat exchanger	33%[17]	Canada
Single- or combi-condensors	7-15%[2]	The Netherlands
Coated glass	25%[6]	The Netherlands
Groundwater source heat pump	60-70%[18]	Canada
Heat pump instead of combi-condensor	38%[6]	The Netherlands
Total saving potential greenhouses (various measures)	77%[6]	The Netherlands

Notes.
1. Stout (1989), Stout and McKiernan (1992). Reflects technical potential at 50% load.
2. De Beer et al. (1994). Reflects technical potential achievable in 2000 using best practice technology.
3. Stout and McKiernan (1992). Actual savings achieved in practice.
4. Stout and McKiernan (1992). Preliminary field test compared with manual selection.
5. Stout and McKiernan (1992), Millar (1995). From small improvements to rankine bottom cycle.
6. De Beer et al. (1994). Reflects technical potential achievable in 2015 using best practice technology.
7. Stout and McKiernan (1992). Technology is still in development phase.
8. Bäumer and Ehlers (1987).
9. Koeller (1987). Reflects potential savings with use of heavy tine cultivator on sand soils to minimum tillage on clay soils; both compared with conventional tillage.
10. Bowers (1992). Reflects potential saving with minimum tillage with corn production.
11. Stout (1989). Potential saving including additional indirect energy for extra herbicides.

12. Stout (1989). Based on experiments with low energy precision application (LEPA) and field tests on different pump types.
13. Sadaphal and Natarajan (1992). Based on efficiency increase in two cases of about 500 pumps.
14. Lazarus et al. (1995). Investments have paybacks to farmers of only 4 month.
15. Baird and Talbot (1992). Heat recovery savings refers to grain drying. Range of savings with optimized fan operation depends on type of dryer.
16. De Beer et al. (1994). Reflects technical potential achievable in 2015 using best practice technology. Percentages refer to savings on energy used for the activity under consideration.
17. CADDET (1993). Energy savings as mentioned in project summaries.
18. CADDET (1993). Energy cost savings as mentioned in project summaries.

Reduced tillage instead of conventional tillage not only saves energy, but also reduces erosion, increases storage of soil moisture, provides labour and cost savings, more double cropping opportunities [Stout,1984] and long term improvement in soil structure/workability [Davies,1987]. A disadvantage is the risk of use of additional herbicides, which causes extra indirect energy input and other environmental impacts. Reduced tillage has a more narrow range of soil to which it is applicable than does conventional tillage [Davies,1987]. Koeller (1987) states that the optimal system is between heavy ploughing (which is energy intensive) and direct drilling (which requires additional herbicides).

Energy consumption of **irrigation** systems is determined by the water requirement of the crop, the field efficiency, the distribution system, the pump and the efficiency of the power source. Energy savings in irrigation can be obtained by more selective application of irrigation and by using more efficient irrigation equipment. More selective application refers to correct timing between water demand of the crop and irrigation, preventing over-irrigation [Stout,1984] and irrigating during suitable weather conditions [Bergen and Biewinga,1992]. In practice large variation can be seen with the pump efficiencies (rated value between 50% for centrifugal pumps and 90% for high volume turbines) and the field efficiencies (between 50% for "big guns" and 90% for "drip/trickle" and low energy precision application, LEPA, systems) [Sloggett,1992]. Evaluations in Pakistan have shown pump set (motor+pump) efficiencies as low as 4% [Vermeiren,1995].

The most energy efficient **drying** is solar drying in the field (if weather conditions are favourable) during the last stages of crop maturity. Many technologies have been developed for solar crop drying after harvesting [Stout,1989]. In general high temperature fast dryers require more energy than low temperature slow dryers [Baird and Talbot,1992].

Savings options in **livestock production** and **horticulture** are largely based on the Dutch situation, where these are very energy-intensive sectors in which many energy conservation studies have been undertaken. Saving potentials will be lower in other countries where these sectors are often less energy intensive and their share in agricultural production is less.

2.1.3 Future agricultural energy consumption

The growth of the activities in the baseline scenario is estimated linear to the growth in cereal production during the period 1989-2010, as projected by the FAO [Alexandratos,1995].[5] Energy use in the business-as-usual scenario is estimated by multilpying the activity growth by the direct energy consumption per unit of product during the period 1980-1990 (see figure 2.2). The growth in ICs is expected to be lower than historical rates following gradual reduction of agricultural subsidies. The growth in the total sector is scaled to the expected growth in cereals production, as cereals are the most important crops (production and surface area). These trends in energy intensity and cereal production are shown in table 2.4. Based on the technical potentials as shown in table 2.3, table 2.4 also presents the estimation of potential energy savings that can be attained for the different types of energy use for the three regions and the resulting overall potential energy saving per region.[6] As the energy consumption figures only comprise commercial fuels, the increasing energy consumption in developing countries is also due to replacing non-commercial fuels and increased mechanisation replacing human and animal energy.

Table 2.4. Main data underlying our scenario estimates.

	DC	EITs	ICs
Share in energy use in 1990 (%)	43	30	28
Annual average growth in energy use per tonne of cereals produced (%)	1.0	0.7	0.5
Projected cereal production annual average growth rate (%)	2.1	0.5	1.1
Projected savings (%): sota-ed/at [1]			
Tractor use	25-40 (0.7-1.1)	30-55 (0.9-1.5)	20-50 (0.6-1.4)
Irrigation	35-45 (1.0-1.2)	25-40 (0.7-1.1)	25-40 (0.7-1.1)
Others	0 -10 (0 - 0.3)	30-50 (0.9-1.4)	30-50 (0.9-1.4)
Overall	24-38 (0.7-1.1)	30-54 (0.9-1.4)	23-50 (0.7-1.4)

Note.
1. Savings are given respectively for the state-of-the-art and the ecologically driven/advanced technology scenario. The first numbers are overall savings potentials between 1990-2010, while the numbers in brackets represent average annual growth.

In the state-of-the-art and the ecologically driven/advanced technology scenarios we assume the savings as projected in table 2.4 in addition to the growth in the business-as-usual scenario. Table 2.5 presents the agricultural energy use in 2020 and its annual average growth between 1990 and 2020 for the three scenarios. The ecologically driven/advanced technology scenario represents a

5 The expected annual average growth for the period 1989-2010 will be extended for the purpose of this study to 1990-2020. The World Bank cereal production projections up to the year 2030 [Crosson and Anderson,1992] (2.3% for DC and 0.4% for other countries) shows that this extension is quite reasonable.

6 For calculation of the overall saving potential the share of the different energy uses in each region has to be known. The ratio between energy for tractors and energy for irrigation has been based on estimations by Stout [Stout,1989], as mentioned in paragraph 2.1.1 (on the basis of number of tractors and irrigated hectares in 1989). The "other" category for ICs has been based on estimation for the USA, being 33% (a.o. for drying and livestock production) [Smil,1992]. On the basis of this, the "other" categories for EITs and DCs are estimated as 20 and 10%. The share of tractors and irrigation then becomes: 44% / 46% (DCs), 69% / 11% (EITs) and 62% / 5% (ICs).

move towards increased use of renewable energy, sustainable farming techniques and introduction of advanced efficient equipment. In the scenario changes to less energy-intensive diets in the regions have not been accounted for. In DCs like China the diet is changing towards higher fractions of dairy, poultry and meat [WRI,1995], while the diet in ICs still contains large quantities of energy-intensive meat products. Changing diets have an impact on agricultural practice, as was shown in a long-term study for Western Europe [WRR,1992].

Table 2.5. Projected direct energy consumption (EJ) in 2020 (with average annual growth between 1990 and 2020 in %/year is given in brackets) in direct agricultural energy consumption.

Scenario	DCs	EITs	ICs	World
1990 Energy use (EJ)	3.7	2.6	2.4	8.7
Business-as-usual	9.2 (3.1)	3.7 (1.3)	3.8 (1.6)	16.7 (2.1)
State-of-the-art	7.2 (2.3)	2.9 (0.4)	3.1 (0.9)	13.1 (1.3)
Ecologically driven / advanced technology	6.6 (1.9)	2.4 (-0.2)	2.5 (0.2)	11.5 (0.8)

2.2 Industry

2.2.1 Introduction

The industrial sector is extremely diverse and involves a wide range of activities including the extraction of natural resources, conversion into raw materials, and manufacture of finished products. This section is derived from a study performed by members of the research team [WEC,1995a]. Although significant potential exists in all industries to improve energy efficiency, our analysis focuses on identifying the energy efficiency potential in five energy-intensive industries. These subsectors, which account for roughly 45% of all industrial energy consumption, are: iron and steel, chemicals, petroleum refining, pulp and paper, and cement. These industries are generally concerned with the transformation of raw material inputs (e.g., iron ore, crude oil, wood) into usable materials and products for an economy.

In 1992, industry accounted for 43% (134 EJ) of global energy use. Between 1971 and 1992, industrial energy use grew at a rate of 1.9% per year, slightly less than the world energy demand growth of 2.3% per year. This growth rate has slowed in recent years, falling to an annual average growth of 0.3% between 1988 and 1992, primarily because of declines in industrial output in the economies in transition. Energy use in the industrial sector is dominated by the industrialized countries, which account for 45% of world industrial energy use. Developing countries and the EITs use 32% and 23% of world industrial energy, respectively (see Figure 2.3).

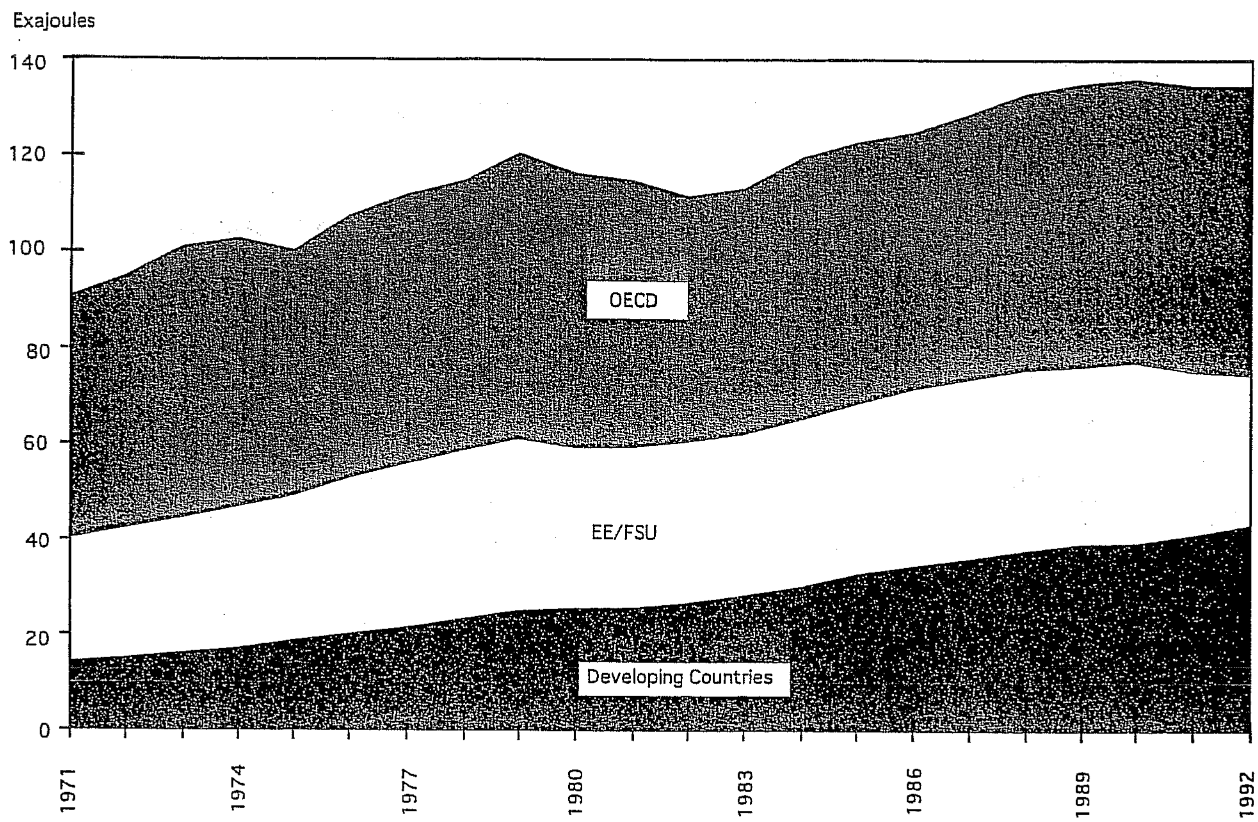

Figure 2.3 Global primary energy use for industry by region, 1971-1992.

Industrialized Countries. Industrial energy consumption in the ICs increased at an average rate of 0.8% per year between 1971 and 1992, from 50 EJ to 60 EJ. The share of industrial sector consumption within the ICs has declined from 42% in 1971 to 36% in 1992. This decline partly reflects the transition toward a less energy-intensive manufacturing base, as well as the continued growth in transportation demand, resulting in large part from the rising importance of personal mobility in passenger transport use [WEC,1995b].

Developing Countries. In 1992, the industrial sector accounted for slightly more than 50% of total primary energy demand in the developing countries. Industrial energy use grew at a rapid annual average of 5.5% in developing countries between 1971 and 1992, jumping from 14 EJ to 43 EJ. China alone accounts for nearly half of total developing country manufacturing energy use. Some of the fastest growth in this sector is in China and in other rapidly-developing Asian countries. Lower energy prices and other factors have also induced the transfer of heavy industry to DCs. The nature and evolution of the industrial sector varies considerably among developing countries. Some economies that are experiencing continued expansion in energy-intensive industry, such as China and India, show relatively unchanging shares of industrial energy use. In other countries, such as Thailand and Mexico, the share and/or growth of the transportation sector dominate [Sathaye and Meyers,1991]. Many smaller countries have remained primarily agrarian societies with modest manufacturing infrastructure.

Economies in Transition. Similar to developing countries, the industrial sector dominates in the EITs, accounting for more than 50% of total primary energy demand. Average annual growth in industrial energy use was 2.2% in the EITs between 1971 and 1988 (from 26 EJ to 38 EJ), with industrial energy consumption declines averaging 4.4% per year between 1988 and 1992 in this region. The EITs have an energy-intensive industrial base, the result of the long-term policy towards materials production that was promoted under the years of central planning.

2.2.2 Technical Potentials

Much of the potential for improvement in technical energy efficiencies in industrial processes depends on how closely such processes have approached their thermodynamic limit. For industrial processes that require moderate temperatures and pressures, such as those in the pulp and paper industry, there exists long-term potential to maintain strong annual intensity reductions. For those processes that require very high temperatures or pressures, such as crude steel production, the opportunities for continued improvement are more limited using existing processes. Fundamentally new process schemes and substitution of materials, changes in design and manufacture of products resulting in less material use and increased recycling, can lead to substantial reduction in energy intensity. Table 2.6 provides examples of energy-efficient technologies and practices for the five industrial subsectors that we assessed. This summary is by no means comprehensive, but rather an indication of the wide range of possibilities that exist within and among industrial sectors for increasing energy efficiency.

Table 2.6 Examples of efficiency improvement measures in energy intensive industry [WEC,1995a]

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

Petrochemicals
Process management and thermal integration (e.g. optimization of steam networks, heat cascading, low and high temperature heat recovery, heat transformers).
Mechanical vapor recompression
New compressor types
New catalysts

Adjustable speed drives
Selective steam cracking membranes
High temperature cogeneration and heat pumps
Autothermal reforming

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

Pulp and Paper
Continuous digester, displacement heating/batch digesters, indirect heating/batch digesters, anthraquinone pulping, chemi-mechanical pulping
Black liquor gasification/gasturbine cogeneration
Oxygen predelignification, oxygen bleaching, displacement bleaching
Tampella recovery system, falling film black liquid evaporation, lime kiln modifications, turbumix system
Improved boiler design/operation (cogeneration), and distributed control systems

Cement
Improved grinding media and linings, roller mills, high-efficiency classifiers in closed-circuit grinding plants, waste heat drying using preheater exit gases, wet process slurry
Dewatering with filter presses and slurry thinners
Low pressure-drop cyclones for suspension reheaters, material recirculation in flash precalciners, kiln combustion system improvements, enhancement of internal heat transfer in kiln, kiln shell loss reduction
Optimize heat transfer in clinker cooler, use of waste fuels, dry-suspension preheater kilns
Dry precalciner kilns, blended cements, cogeneration, high-temperature ceramic filters for exhaust
Modified ball mill configuration, particle size distribution control, improved grinding media and linings, high-pressure roller press for clinker pre-grinding, high-efficiency classifiers in closed circuit plants, roller mills

Table 2.7 presents an overview of the main results of selected studies for the technical potential of energy efficiency improvement for the five industrial subsectors. Although in some of these potentials economic constraints have already been taken into account, generally the economic potential for energy efficiency improvement will be lower (see Chapter 4).

Table 2.7 Technical potential for energy efficiency improvement in selected industrial subsectors.

Sector	Potential	Country/Region
Steel		
	2-30%[1]	U.S.A.
	26-51%[2]	ICs
	46-57%[2]	EITs
	36-52%[2]	Developing Countries
	39-52%[3]	Canada
Chemicals (savings include feedstocks)		
Ethylene	5-12%[4]	Netherlands
	2-11%[1]	U.S.A.
Ammonia	1-35% (21% Avg.)[5]	Europe
	16-34%[6]	EITs
	20-30%[7]	Southeast Asia
Chlorine	23-27%[8]	ICs

Petroleum Refining		
	20-28%[1]	U.S.A.
	1-27% (15% Avg.)[5]	Europe
Pulp and Paper		
	13-41% (25% Avg.)[5]	Europe
	33%[9]	Netherlands
	50-75%[10]	Netherlands
	20-30%[11]	Europe
	20-25%[12]	India
	15-30%[7]	Southeast Asia
	24%[13]	Canada
	30-49%[1]	U.S.A.
Cement		
	26-55%[1]	U.S.A.
	4-36%[14]	ICs
	30-57%[14]	EITs
	13-41%[14]	Latin America
	11-31%[15]	China

Notes.
1. DOE, Office of Industrial Technologies (1990). Reflects 1990-2010 scenario results.
2. WEC (1995a). Reflects technical potential for 1988 using best practice technology.
3. WEC (1995a). Reflects 1990-2010 scenario results for Canada reported in an appendix.
4. Worrell et al. (1994a). Reflects technical potential for 1988 using best practice technology.
5. Worrell et al. (1994b). Reflects technical potential for 1989 using best practice technology.
6. Worrell and De Beer (1995). Reflects technical potential for 1989 using best practice technology.
7. Ishiguro and Akiyama (1994).
8. Smit et al. (1994). Reflects technical potential achievable in 2015 using best practice technology.
9. De Beer et al. (1993). Reflects technical potential 1985-2000 achievable using best practice technology.
10. De Beer et al. (1993). Reflects technical potential savings to reduce steam demand of drying section by 2020 to 2030.
11. Bateman (1992). Reflects comparison of current average to best available technology.
12. Tata Energy Research Institute (1994). Reflects technical potential using current best practice technology.
13. WEC (1995a). Reflects 1990-2010 scenario results.
14. Worrell et al. (1995).
15. Liu et al. (1995). Reflects near-term scenarios that include economic considerations.

Iron and Steel. Steel is used for a broad range of materials and products. As countries industrialize there is an increased demand for steel products to support expanding economic infrastructure needs. Industrialized countries tend to demand high-value added steel products that are used in the automotive and metals fabrication industries. The energy intensity of iron and steel production is affected by these different product mixes. However, the types of technologies and processes used to produce steel account for the greatest fluctuation in energy intensity. Compared to the oldest existing steel production technology of the open hearth furnace (OHF), both the basic oxygen furnace (BOF) and the electric arc furnace (EAF) use less energy per tonne of steel produced. Replacing OHF with BOF results in an intensity drop of 1-3 GJ/tonne, although the potential reduction in energy use is highly dependent on the molten iron/scrap ratio. The relative shares of steel production technologies have a large impact on a country's technical potential for improving energy efficiency. EAF technology uses less energy since the process is based on the use of scrap iron, reducing the need to produce pig-iron in the blast furnace. The use of EAF worldwide will be constrained by the scrap availability. Scrap availability is determined by the scrap recovery rate, the availability and cost of scrap and scrap substitutes, and the ease of transport and trade of scrap. Even so, the use of EAF technology grew to nearly one-third of overall production globally, between 1982 and 1993. The substitution of ingot casting by continuous casting has greatly improved product yield and energy efficiency.

Within the steel industry, a variety of technologies and practices exist that improve energy efficiencies (see Table 2.6). Even among ICs, considerable potential (25-50%) exists to improve plants to best practice levels. Similar or greater potentials exist for developing countries (see Table 2.7).

Chemicals. The chemicals industry is complex, encompassing the production of more than 50,000 chemical compounds. The main products are plastics, synthetic rubber, soaps, paints, industrial gases, fertilizers, pesticides, and pharmaceuticals. We focus our analysis on four energy-intensive production processes: ethylene, ammonia, methanol, and chlorine. The demand for, and production of, these products is expected to grow significantly in developing countries over the next three decades. Energy efficiency potentials for these processes can help to approximate potentials for the industry as a whole.

Ethylene. The production of petrochemicals such as ethylene, propylene, and aromatics by steam cracking of hydrocarbon feedstocks is the single most energy-consuming process in the petrochemicals sector. The high energy requirement reflects the heating, separation and purification of the hydrocarbon feedstocks and products. Heavier feedstocks such as naphtha can require nearly twice the energy to crack as lighter feedstocks (e.g. ethane), but the choice of feedstock is determined by market factors such as the cost of feedstocks and the market prices of ethylene and its various co-products.

Aside from feedstock use, improving process integration, energy recovery, and process control hold the greatest potential for improving efficiency. Longer term improvements will focus on new catalysts and processes that greatly reduce energy requirements, such as a recent process that eliminates refrigeration systems for ethylene production [Anon.,1995].

Current statistics suggest that energy use for ethylene production (including feedstock consumption) varies widely: 68 GJ/tonne in the U.S., 58 GJ/tonne in the Netherlands, and 73-90 GJ/tonne in China [OTA,1993; Worrell et al.,1994c; China Energy Research Society,1993; Yang and Zeng;1994]. Differences in both feedstock composition and technology account for the significant range of energy use. Compared to best practice technologies, potential improvements in energy efficiency in the U.S. and Europe ranged from 2 to 12%. Given the strong demand expected for ethylene-based products, even small efficiency improvements may reduce energy use in this area significantly.

Ammonia. The two main production processes for the manufacture of hydrogen for ammonia are the partial oxidation of hydrocarbons and steam reforming of natural gas. Ammonia production technology has significantly improved in the last three decades, improving economies of scale and also energy efficiency. The use of natural gas as a feedstock for steam reforming is the most efficient technology, with best practice methods able to achieve specific energy consumptions (SEC) of 28 GJ/tonne (including feedstock). Recent estimates for energy use for ammonia production in Europe ranged from 33 to 44 GJ/tonne, depending on the country [Worrell et al.,1994b].

For developing countries, SEC can vary dramatically depending on the type of technology installed. In China, for example, where ammonia production is still dominated by small and medium-size plants using oil and coal feedstocks, SECs can be 20 to 25% higher than the large-scale plants of recent design. A number of technologies exist that would allow manufacturers to achieve SECs of 28 GJ/tonne including the optimization of heat recovery, the recovery and separation of hydrogen, improved CO_2 separation, low pressure loops, pre-reforming, and improved process management, although it is sometimes difficult to incorporate these as add-ons to existing plants. More advanced technologies such as direct oxidation, autothermal reforming, and advanced reactors that increase conversion efficiencies can reduce energy requirements even closer to the theoretical minimum of 19.1 GJ/tonne, although lack of knowledge and the cost of technology development is an important limiting factor [De Beer et al.,1995]. The long-term energy intensity is estimated at 22-24 GJ/tonne [De Beer et al.,1995].

Methanol. Methanol is used primarily for the production of formaldehyde and for reformulated gasoline additives, such as MTBE. SEC for methanol production using today's newest technology (low pressure synthesis) is 28 to 33 GJ/tonne [Anon.,1995]. Consumption can vary depending both on feedstock and technology used for production. Many of the technologies and practices identified under ammonia production can also be applied for methanol, although less data on technical energy savings potential are available for this product.

Chlorine. Chlorine is used in a wide variety of chemical products, and the largest end-uses are polyvinyl chloride (PVC) and as a bleaching agent in pulp and paper manufacturing. Chlorine is produced through the electrolysis of sodium chloride which requires significant amounts of electrical energy. Typically, electricity requirements for chlorine vary between 2850 and 3500 kWh/tonne depending on the cell type used. The evaporation step can also require a significant amount of energy, especially for the diaphragm cell process. The membrane cell technology requires less energy than the diaphragm cell and less energy is required for evaporation. Theoretically, the minimum energy requirement to produce one tonne of chlorine in electrolysis is 1680 kWh/tonne using advanced membrane technology [Smit et al.,1994].

As the descriptions indicate, significant potentials still exist to improve the energy efficiency in bulk chemicals production. A large number of the energy process improvements for heating, cooling, electrolysis, distillation, and power generation and other energy services, are not specific to one product but could have significant cross-cutting effects for reducing energy requirements. Such investment synergies could likely play a key role in developing a future energy efficiency investment strategy for the sector.

Petroleum Refining. The consumption of petroleum products has paralleled overall energy consumption in both industrialized and developing countries with middle distillates (such as diesel fuel and naphtha) and gasolines accounting for the largest share of consumption. Given the capital intensive nature of developing a downstream refinery infrastructure, ICs have historically accounted for most of the world's capacity followed by the EITs. However, the most rapid capacity growth is slated to take place in developing countries, especially Asia, to meet the growing demand. Although the refining process is less energy intensive than the production of steel and bulk chemicals, the sheer throughput volume makes petroleum refining one of the three largest energy consuming sectors in the U.S. and Europe.

An important factor determining the aggregate intensity of oil refining is the complexity of the refinery. As the global demand for gasoline and other middle and high-end distillates grew, so too has the energy requirements for production. Modern complex refineries have much higher energy requirements for conversion and finishing processes than simple distillation refineries mainly due to the inclusion of hydrogen manufacture, recovery of sulfur, and hydrotreating. In addition, heavier or more sour crudes require more energy to process into finished products.

Significant process improvements have occurred in refining reducing energy requirements in particular processes, through waste heat recovery and the development of new process technologies. Technology to more fully utilize crude feedstock has also improved thereby reducing refinery waste streams. These factors combined have shown that even though refinery complexity and the demand for cleaner products in ICs increased over the last two decades, the energy required to produce a tonne of product has fallen on the order of 1 to 2% annually. Aggregate energy intensities have varied significantly in different regions. For refineries in developing countries of comparable complexity to efficient IC refineries, fuel use to process the crude can run up to 15 to 20% of the intake fuel, almost double that of modern refinery systems [Ghamarian,1995]. State-of-the-art refineries require 3.8 GJ/tonne for gasoline production and studies have shown that in the U.S. and Europe potential improvements on the order of 15-20% are achievable by incorporating state-of-the-art technologies [Worrell,1994b; DOE,1990]. Greater potentials exist for many refineries in the EITs and developing countries.

Pulp and Paper. Per capita consumption of paper and paper products follows a country's per capita gross domestic product. Thus, the largest per capita consumers of these products are the ICs, and the smallest per capita consumers include India, China, Mexico, and Brazil. As economies industrialize, consumption of paper will increase, as evidenced by recent high growth rates in paper consumption in South-East Asia (see chapter 3).

A recent analysis of SECs for production of nine pulp and paper products in 11 OECD countries found a decline of 22% (at an average annual rate of 1.4%) between 1973 and 1991 [Farla,1995]. The most important factors affecting the amount of energy consumed in the paper industry worldwide are the amount of self-generated fuels used, the pulping process, and the share of waste paper. Self-generated fuels such as bark and black liquor, provide over 50% of the energy used in both the U.S. and Canadian pulp and paper industries [Pulp & Paper International,1995].

The share of waste paper as a raw material input influences the amount of energy consumed at a mill [De Beer et al.,1993]. Only 10 to 30% of the energy required to make chemical pulp from wood is needed to produce pulp from waste paper [Ishiguro and Akiyama,1994]. The production of primary newsprint from mechanical pulp in the U.S. requires about 25 GJ/tonne, while the production of secondary newsprint from waste paper only requires about 15 GJ/tonne, saving about 10 GJ/tonne of mostly electric energy [Elaahi and Lowitt,1988]. Worldwide, recycling has grown from recovery of 30% of paper and paperboard in the early 1980s to 35% in 1989. The United States paper industry consumed 26.5 Mt of recovered paper in 1994, 31.5% of the industry's papermaking fiber share. In 1990, 52% of the paper and paperboard consumed in Japan was recycled for making paper products [Ishiguro and Akiyama,1994]. Use of waste paper in the European Union is about 50%, and ranges from 27% in Belgium to 69% in the Netherlands [VNP,1990].

Cement. Worldwide, cement production increased at an average of 3.7% annually between 1970 and 1990. Developing countries surpassed the other regions with an average growth rate of 8.5% per year for the period, compared to 1.4% and 1.6% per year for the ICs and EITs, respectively. This is due to the increased urbanization and the higher population growth in cities (compared to the country average) in DCs. The largest annual growth rates were seen in Indonesia, China, and Saudi Arabia. Production in China has grown dramatically in recent years, increasing at an average of more than 16% per year between 1990 and 1994. Production almost doubled since 1988 [WEC,1995a]. Average SECs for cement production range from about 2 to 7 GJ/tonne, depending on the country and process used [Worrell, et al.,1995c]. The intensity of cement production is influenced by the share of dry vs. wet process used in production, the clinker-to-cement ratio, and the type of kiln (rotary vs. vertical). In the United States, the dry process typically uses between 3.5 and 4.5 GJ/tonne of cement, while the average wet process uses over 5.2 GJ/tonne [DOE OIT,1990]. Estimates vary, but a full conversion from a long-wet kiln to a preheater/precalciner kiln yields fuel savings of 45% or more [Fog and Nadkarni,1983]. In 1980, only about 35% of world cement was still produced by the wet process. While Germany and France use only 3% and 10% wet process, respectively, use hovers around 50% in developing countries and is as high as 85% of production in the FSU [Lazarus,1993]. In the U.S., the wet process was used for 35% of production in 1990 [van der Vleuten,1994].

The energy intensity of cement production is reduced directly proportional to the amount of additives used relative to clinker. Some of the additives that can be blended with clinker to reduce the energy intensity of cement production include blast furnace slags, fly-ash, and natural pozzolanes (volcanic material). Clinker to cement ratios are typically between 70 and 90% in Eastern Europe and between 80 and 90% in Latin America. The U.K., U.S., Denmark, Ireland, and Portugal all have ratios above 90%, while the Netherlands has a remarkably low ratio of 27% [Worrell et al.,1995]. Rotary kilns are typically more efficient than small-scale vertical kilns. About 70% of worldwide capacity is rotary kilns (with or without preheater or precalciner systems). Vertical kilns, which are usually used in more remote areas where large scale plants are not economically viable, can be found in India and China.

2.2.3 Scenarios of Global Industrial Energy Use

Three energy use scenarios for the period 1990-2020 were developed (see Table 2.8) [WEC,1995a]. The business-as-usual scenario assumes continued use of the mix of current technologies and reflects current trends. The state-of-the-art scenario assumes the replacement of existing stock with the current most efficient technologies available. The ecologically driven/advanced technology scenario assumes that technologies that are not yet commercially available are adopted. Under the business-as-usual scenario, global industrial energy use grows at a rate of 1.4% per year, increasing from 136 EJ in 1990 to 205 EJ in 2020. Sectoral production levels increase at annual rates between 1.7 and 2.7%, while energy intensities decline at a rate of about -0.5% per year. The largest growth in both production and energy use is seen in the developing countries.

Growth in global industrial energy use slows to 0.8% per year in the state-of-the-art scenario, with energy consumption in 2020 dropping to 173 EJ. Energy intensity decreases with about -1.1%/year. An even more dramatic reduction in energy use is seen in the ecologically driven/advanced technology scenario, where annual growth is less than 0.1% and total industrial energy use is 139 EJ, roughly the same as industrial energy use in 1990. Production levels are assumed to be the same as those in the previous two scenarios except in the petroleum refining sector where production declines are because of policies that reduce oil demand in industry as well as in the transportation sector. The savings range from -1.5% per year for iron and steel, petroleum refining, and pulp and paper to -2.4% per year for cement.

2.3 Buildings

2.3.1 Introduction

Approximately 36% of world primary energy is consumed by commercial and residential buildings. Global buildings energy use was 104 EJ (commercial fuels only) in 1992, with ICs buildings consuming 58% of total world buildings energy use, followed by developing countries (22%) and the EITs (20%). Energy use in residential buildings is about twice that of commercial buildings worldwide. However, energy demand in commercial buildings has grown about 50% more rapidly than demand in residential buildings for the past two decades. Between 1971 and 1992, average growth in energy use for buildings was 2.7% per year, faster than the global average energy use. Average annual growth rates in buildings sector energy consumption between 1971 and 1992 were slowest in the OECD (1.9%) and much more rapid in the EITs (3.0%) and DCs (6.2%) (see Figure 2.4). Growth in residential buildings energy use in developing countries slowed recently, dropping to 2.7% per year since 1988. Commercial buildings energy use in this region jumped to 8.7% per year during the same period. Average declines of 3.8% per year were experienced between 1988 and 1992 in the EITs.

Table 2.8 Future industrial energy consumption (in EJ) for three scenarios until the year 2020.

Sector/ Region		Business-as-Usual		State-of-the-Art		Ecologically Driven/ Advanced Technology	
	Energy 1990	Energy 2020	Growth (%/yr)	Energy 2020	Growth (%/yr)	Energy 2020	Growth (%/yr)
Iron and Steel							
ICs	7.6	8.0	0.2	7.1	-0.3	6.6	-0.5
EITs	6.2	4.9	-0.8	4.0	-1.4	3.4	-1.9
DCs	4.8	12.5	3.3	11.3	2.9	9.6	2.3
Total	18.6	25.4	1.1	22.4	0.6	19.5	0.2
Chemicals-Ammonia							
ICs	0.4	0.3	-1.1	0.3	-1.9	0.2	-2.8
EITs	0.7	0.6	-0.7	0.5	-1.2	0.4	-1.8
DCs	0.6	1.3	2.8	0.9	1.6	0.7	0.4
Chemicals-Ethylene							
ICs	0.7	1.3	2.1	1.1	1.6	0.9	1.0
EITs	0.2	0.2	0.2	0.2	-0.6	0.1	-1.1
DCs	0.1	0.5	4.3	0.4	3.4	0.3	2.9
Total [1]	4.2	6.1	1.2	5.0	0.5	4.1	-0.1
Petroleum Refining							
ICs	5.1	6.0	0.5	5.3	0.1	4.2	-0.6
EITs	3.2	3.6	0.4	2.9	-0.4	2.2	-1.3
DCs	3.6	7.2	1.3	6.2	1.8	3.7	0.1
Total	12.0	16.8	1.1	14.5	0.6	10.1	-0.6
Pulp & Paper							
ICs	4.0	5.4	1.0	4.3	0.2	3.7	-0.6
EITs	0.5	0.6	0.8	0.5	0.3	0.4	-0.4
DCs	1.3	5.1	4.7	4.4	4.3	3.6	3.5
Total	5.7	11.1	2.2	9.2	1.6	7.7	1.0
Cement							
ICs	1.6	1.7	0.4	1.5	-0.2	1.2	-0.9
EITs	1.3	1.4	0.2	1.1	-0.6	0.8	-1.8
DCs	3.3	8.4	3.2	6.6	2.3	4.6	1.1
Total	6.2	11.5	2.1	9.2	1.3	6.6	0.2
Total[1]	135.8	205.0	1.4	172.5	0.8	138.6	0.1

1. Methanol and chlorine are not shown. The total reflects the total for the total chemical industry.
2. Estimated using a scaling factor of 44.7 on basis of the five sub-sectors.

Industrialized countries. Residential energy use in ICs grew 1.4% per year between 1971 and 1992. Population increases as well as decreasing household size resulted in increased energy use. In addition, demand for various residential services, particularly for central air conditioning, appliances, space and water heating increased. Even though there has been a significant reduction in the energy required to deliver various services, particularly in technologies such as space heating furnaces, refrigerators, and lighting systems, a study of ten ICs showed that overall energy use for electric appliances grew between 1973 and 1992 because of the large increases in appliance ownership [Schipper et al.,1996]. Growth in energy use in commercial buildings between 1971 and 1992 averaged 2.6% per year due to an increase in the demand for services. Data for ten OECD countries show that electricity use increased 2.2% per year from 1970 to 1990, because of increases in electric heating, computers and other office equipment [Schipper and Meyers,1992].

Developing countries. There has been a steady increase in the relative share of buildings energy consumption in DCs, from about 25% in 1971 to about 30% in 1992. This share is expected to rise in the future due to rapid economic growth and population increases in many DCs. From 1971 to 1992, purchased energy consumption for commercial and residential buildings in developing countries grew 6.7% per year and 5.7% per year respectively. Per-capita energy consumption for buildings, particularly in Asia and Latin America, has grown faster than either population or GDP. Residential buildings in DCs account for 78% of buildings energy consumption, and the share would be even higher if biomass energy were included. In this report we limit the discussion to commerical fuels. Because of the strong correlation between income level and the ownership of appliances, demand for energy services such as refrigeration, home entertainment (television), and space conditioning will increase as DC-economies expand. Increasing urbanization and the substitution away of traditional fuels will increase purchased energy demand as well.

Economies in transition. From 1971 to 1988, building energy use in EITs grew 4.7% per year. Buildings in the former Soviet Union require 50% more energy to heat a square meter of floor space (after correcting for weather) than buildings in the US [Cooper and Schipper,1991]. In the residential sector, the largest end-uses are space-heating, water heating, and cooking. For commercial buildings, energy use per unit of floorspace can be double that of ICs as space conditioning systems are poorly regulated and the leakage from building envelopes is often high. The economic transition since 1988 has led to decreasing residential and commercial building energy use of 4.6% and 2.2% per year, respectively.

2.3.2 Technical Potentials

The buildings sector is complex and includes a wide variety of specific energy applications such as cooking, space heating and cooling, lighting, food refrigeration and freezing, office equipment, and water heating. These applications are so-called end-use services, emphasizing the concept that what is important is not the energy consumed but the service delivered: cooked food, a warm space, or a lit office. The most important factors that drive energy consumption in buildings are population, economic growth, the type of energy services demanded, and the energy used to provide those services. For example, efficient building technologies such as energy-efficient lighting or air conditioning reduce the energy required to provide the same level of lighting or cooling in a building. Table 2.9 lists examples of efficient building technologies or practices.

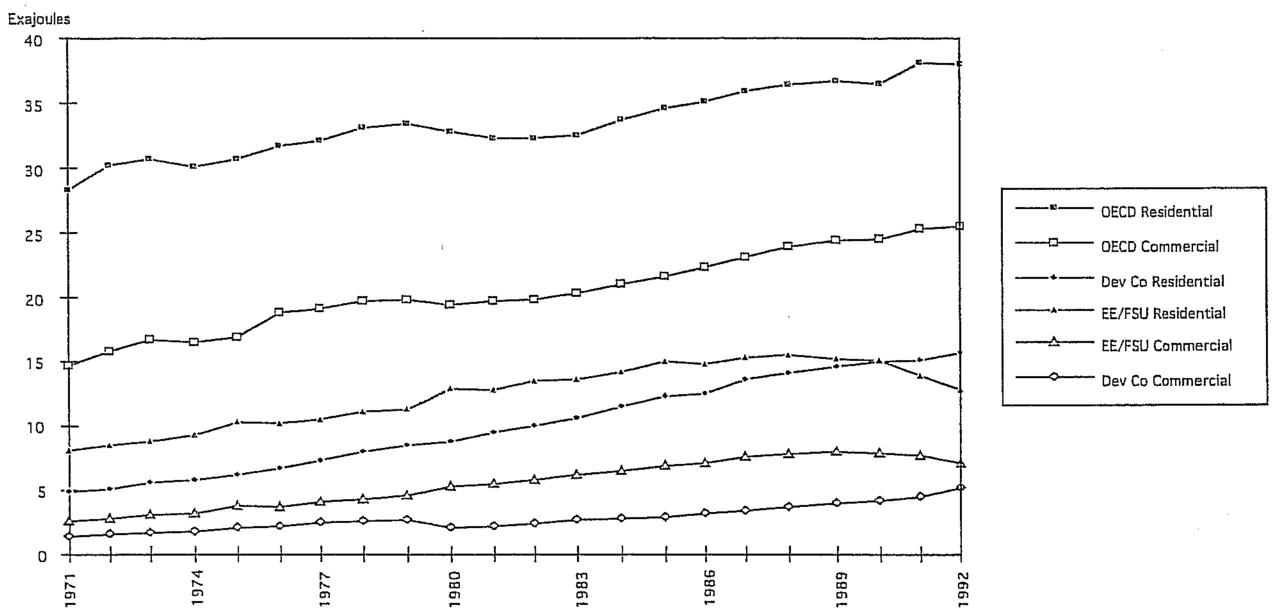

Figure 2.4 Building energy use in various regions in the period 1971-1992 [WEC,1995a].

Table 2.10 presents an overview of the results of selected studies for the technical potential of energy efficiency improvement in residential and commercial buildings. Potential savings range from 23 to 76% depending upon the sector, the country or region, and other assumptions. Economic potentials, which only include those technologies and practices that are cost-effective, are generally lower (see Chapter 4).

Table 2.9. Summary of selected energy-efficient technologies and practices for buildings [WEC,1995a].

Service	Technology/Practice
Building Envelope	Energy-efficient windows Insulation (walls, roof, floor) Reduced air infiltration
Space Conditioning	Gas-fired, condensing furnaces High efficiency heat pumps Air conditioner efficiency measures (e.g., thermal insulation, improved heat exchangers, advanced refrigerants, more efficient motors, see below) Centrifugal compressors, efficient fans and pumps, and variable air volume systems for large commercial buildings
Appliances	Advanced compressors, evacuated panel insulation (refrigerators) Use of horizontal axis technology (clothes washers) Higher spin speeds in washing machine/spinner, heat pump dryers
Cooking	Improved efficiency of biomass stoves (developing countries) Efficient gas stoves (ignition, burners)
Lighting	Compact fluorescent lamps Improved phosphors Solid state electronic ballast technology Advanced lighting control systems (incl. daylighting and occupancy sensors) Task lighting
Motors	Variable speed drives Size optimization Improvement of power quality Use of synchronous and flat belts Controls
Building energy management systems	

Space Conditioning. Energy consumed for space conditioning (heating, cooling, and ventilation) can be reduced through improved building practices (see below), increased efficiency of space-conditioning equipment and improved control. In the EITs in many buildings controls are not available at all. Modern gas-fired warm-air furnaces in the US have minimum efficiency requirements of 78%. More advanced condensing boilers have efficiencies of 90 to 97% [OTA,1992c]. Electric heat pumps typically consume about half as much electricity for heating as electric resistance-based systems [Koomey et al.,1991]. High-efficiency heat pumps are available that are about 25% more efficient than standard heat pumps based on field tests [Schaper et al.,1990]. Gas fired heat pumps are available for commercial buildings (and soon for residential buildings) offer large efficiency improvement. Technical efficiency improvements for district heating systems include better insulation of pipes and improvement of the operation and control of heating systems, which is especially important in EITs.

Table 2.10 Technical potential for energy efficiency improvement in residential and commercial buildings.

Sector	Potential	Country/Region
Residential	48%	USA [1]
	27-46%	USA [2]
	29%	USA[3]
	36%	USA [4]
	60%	France, Germany, Italy, The Netherlands, UK [5]
	42-76%	The Netherlands [6]
	31%	Brazil [7]
Commercial	38%	Brazil [7]
	23-49%	USA [2]
	55%	USA [4]
	65%	France, Germany, Italy, The Netherlands, UK [5]
	41-74%	The Netherlands [6]
	60%	Slovak Republic [8]
	45-56%	Thailand [9]
Residential and Commercial		
	45%	USA [4]
	43%	Sweden [10]

Notes.
1. Koomey et al. (1991). Technical potential for electricity relative to a frozen efficiency.
2. Faruqui et al. (1990). Technical potential for electricity in the year 2000.
3. DOE EIA (1990). Technical potential for total energy use in the year 2010.
4. Rosenfeld et al. (1993). Technical potential for electricity in 1989 relative to frozen efficiency.
5. Krause et al. (1995). Technical potential for the year 2020.
6. De Beer et al. (1994). Technical potential for total energy use in the year 2000 and 2015 respectively relative to frozen efficiency.
7. Geller (1991). Technical potential for electricity in the year 2010.
8. Kaan et al. (1995). Technical potential for fuels (heating) in the near term.
9. Busch (1990). Economic potential for electricity savings.
10. Bodlund et al. (1989). Technical potential for electricity relative to frozen efficiency.

Efficiency improvements for air conditioners include better thermal insulation, larger and/or improved heat exchangers, higher evaporator coil temperatures, advanced refrigerants, more efficient motors, dual-speed or variable speed compressors,and more sophisticated electronic sensors and controls [Morgan,1992; Geller,1985]. In the US, the most efficient models on the market are 49% more efficient than the average new model [Levine et al.,1992]. Energy for air and water transport within buildings can be reduced by employing efficient motors and impeller designs, by good duct and pipe design, and by allowing fans and pumps to operate at speeds that closely match thermal loads. Energy savings between 30 and 80% can be realized with a variable-air-volume HVAC system with variable-speed drives on the fans [Usibelli et al.,1985].

Building Envelope. Energy use can be reduced with building designs that include proper orientation, adequate insulation levels, proper sealing, overhangs, and high-quality windows. In the US, an estimated 25% of residential heating and cooling energy use is associated with losses through windows [Bevington and Rosenfeld,1990]. A complete change of the stock to the most cost-effective, currently available energy-saving window systems is estimated to reduce the energy losses through windows by two-thirds [Frost et al.,1993]. Improvements in the thermal characteristics of windows and increases in wall and ceiling insulation in residential buildings in China can reduce energy use by 40% relative to mid-1980s practice while allowing for a considerable increase in indoor temperatures [Huang,1989]. A West German study that evaluated homes of different vintage in five building types found that investments saving 40% of baseline heating energy would be cost-effective [Ebel et al.,1990]. In the US, a government study estimated that energy savings of 30-35% could be attained over the 1990-2010 period through retrofits in dwellings built before 1975 [EIA,1990].

So-called "low-energy" homes have demonstrated the technical feasibility of reducing heating requirements to very low levels through use of high levels of insulation, passive solar design techniques, and other measures [CADDET,1995], but these have achieved only limited market penetration to date. Adoption of Swedish building practices, which rely heavily on assembly from factory-built components, in the rest of Western Europe and North America would bring a reduction of at least 25% in the space heating requirements of new dwellings relative to those built in the late 1980s [Schipper and Meyers,1992].

Appliances. The average efficiency (measured in terms of refrigerated volume per unit of electricity consumption) of new refrigerators in the US has increased by almost 200% from 1972 to 1994 [AHAM,1995]. Standards applied in 1993 reduced electricity use by 28% relative to the average model produced in 1989 [Turiel et al.,1991], and proposed 1995 standards could reduce electricity use another 25-30% [DOE,1995c]. The state-of-the-art model has a unit energy consumption (UEC) of 710 kWh/year, 40% better than the stock average UEC of 1200 kWh/year [Levine et al.,1992]. Advanced compressors, evacuated panel insulation, and other features have the potential to produce commercial and cost-effective refrigerators that have UECs between 200 and 500 kWh/year [Levine et al.,1992]. Similar results are found for European refrigerators and freezers [Lebot et al.,1991; GEA,1993]. Energy-efficient refrigerators are built and marketed in DCs as well. For clothes washers and dishwashers, analysis for the US found cost-effective options to reduce energy use by 30% (including energy to heat water) [DOE EIA,1990]. For clothes washers, a change from vertical-axis to horizontal-axis reduces energy use by about two-thirds relative to the baseline (mainly due to much lower use of hot water). For clothes dryers, the cost-effective reduction in energy use is only 15%, but much greater savings (about 70% relative to a conventional electric clothes dryer) are possible through use of a heat pump dryer [Levine et al.,1992].

It is estimated that energy-saving power management software for personal computers, monitors, printers, copiers, and fax machines can save 22% of projected US commercial sector electricity use by these products in 2010. Use of advanced technologies such as LCD screens and CMOS chips coupled with the use of less energy-intensive printers can lead to savings of almost 60% [Koomey et al.,1995].

Cooking Equipment. In the industrialized countries, there is relatively limited potential (10 to 20%) to improve the energy efficiency of primary cooking devices. The state-of-the-art electric range, for example, has a UEC of 700 kWh/year, only 10% better than the stock UEC of 770 kWh/year. Advanced electric ranges are estimated to have UECs 35-50% lower than current stock [Levine et al.,1992]. In developing countries, improved cooking stoves can reduce the fuel used for cooking a standard meal by 30 to 40% [Leach and Gowan,1987]. An additional 50% fuel savings can be realized by switching to a kerosene stove [Dutt and Ravindranath,1993]. Cookstove dissemination programmes in China, India and Kenya have been effective, and not only reduced energy use but also improved health and social conditions [Kammen,1995].

Lighting. Incandescent lamps still represent the majority of lamps. Replacement by (compact) fluorescent lamps can save up to 80% of energy use [De Beer et al.,1994], depending on the number of incandescent lamps to be replaced and CFLs installed. Five options are available to improve fluorescent lamp efficiency: higher surface area to volume ratio, reduced wattage, increased surface area, better phosphors, and reflector lamps [Mills and Piette,1993]. More efficient electromagnetic ballasts reduce ballast losses to about 10%. Solid state electronic ballasts cut ballast losses even further and also increase lamp efficiency due to high-frequency operation. This can increase the efficiency of the ballast/lamp system by approximately 20 to 25% relative to that with an ordinary ballast [Verderber,1988]. In addition, lighting energy use can be reduced through use of lighting controls and improved lighting fixtures [Mills and Piette,1993]. A number of energy-saving lighting controls are now on the market including multi-level switches, timers, photocell controls, occupancy sensors, and daylight dimming systems. These measures typically result in savings of 10 to 15% for photocell controls, 15 to 30% for occupancy sensors, to 50% in perimeter zones for daylighting systems [Mills and Piette,1993; Eley Associates,1990; and Rubenstein and Verderber,1990]. "Task lights" (small lights that illuminate only the work surface) can be used, so that general lighting levels can be reduced. It has been estimated that lighting energy use in the residential and commercial sectors can be reduced by 47 and 69% respectively [Nadel et al.,1993].

Studies of cost-effective energy savings for lighting in commercial buildings in different countries have produced a range of savings estimates: 35% for the US [Atkinson et al.,1992]; between 36 and 86% for five countries in Western Europe [Nilsson and Aronsson,1993]; 70% in Thailand [Busch et al.,1993]; 22% in Brazil [Jannuzzi et al.,1991]; and 35% in India [Nadel et al.,1991a].

Motors. Variable speed drives that modify the power going into the motor, allowing the speed to be varied in proportion to the amount of motor power needed, reduce electricity use by 15 to 30% in buildings [Nadel et al.,1991b]. Improvement of power quality problems (voltage dips and rises, phases out of balance, distorted electrical sine waves) can save 1 to 15% [Lovins et al.,1989]. Optimal sizing of motors, pumps, fans, compressors and cables can also reduce losses. A good maintenance program can reduce motor electricity use by up to 10 to 15% [Ibanez,1978]. Proper temperature regulation and use of a mechanical stripping process during motor rewinding can eliminate further losses [Dreisilker,1987]. An analysis for the US estimated that electric motor energy use in industry and buildings can be reduced by 16 to 40% by applying a variety of the measures discussed [Nadel et al.,1991b]. Another study estimated an even higher savings potential of 44 to 60% [Lovins et al.,1989].

Water Heating. Use of hot water can be reduced by installing water saving shower heads and flow limiters, saving on water and energy for water heating [De Beer et al.,1994]. State-of-the-art electric water heaters have UECs of 1200 kWh/year, 68% better than the average stock UEC of 3800 kWh/year. Advanced electric water heaters, using electric heat pumps have UECs of 800-1000 kWh/year [Abrams,1992; Levine et al.,1992]. Electric heat-pump water heaters consume about 50 to 70% less electricity than electric resistance water heaters [Geller,1986]. Exhaust-air heat pumps in which the heat from the exhaust air of ventilation systems is pumped into the stored hot water are another promising option. In Eastern Europe, separate provision of domestic hot water from space heating can contribute energy savings by reducing the enormous summertime losses in large-scale heat systems that provide only domestic hot water. Gas based water heat systems (including automatic ignition) can save primary energy compared to electric systems [De Beer et al.,1994]. Solar boilers can be used in many climatic zones, also in North-West Europe [De Beer et al.,1994], and save approximately 40% on energy use for water heating.

Building Energy Management Systems. Building energy management and control systems regulate the operation of heating, ventilation, air conditioning, and lighting in buildings. These systems range from simple point-of-use timers to complex microprocessor-based systems that can minimize unnecessary equipment operation and provide other functions such as economizer cycling or varying supply air or water temperatures depending on climatic conditions and limit peak electrical loads by selectively switching off or cycling certain loads. It is estimated that computerized energy management equipment typically provides 10 to 20% energy savings [Geller,1988]. A study in Texas (USA) identified potential annual energy savings of 23% of total building energy costs in 35 commercial buildings and 104 schools [Liu et al.,1994].

2.3.3 Scenarios of Global Buildings Energy Use

Three scenarios for the period 1990-2020 were developed (see Table 2.11) [WEC,1995a]. The business-as-usual scenario assumes continued use of the mix of current technologies and reflects current trends. The state-of-the-art scenario assumes the replacement of existing stock with the current most efficient technologies available. The ecologically driven/advanced technology scenario assumes that technologies that are not yet commercially available are adopted. Under the business-as-usual scenario, global buildings energy use grows at a rate of 2.4% per year, increasing from 103 EJ in 1990 to 207 EJ in 2020. Of the 104 EJ increase in energy use in buildings projected to occur between 1990 and 2020, 21 EJ is in the ICs, 45 EJ is in the EITs, and

38 EJ is in developing countries. The relatively higher energy growth in the EITs results from a shift from a heavy industrial to a more consumer-based economy, with considerable growth in the number and floor area of residential and commercial buildings in the region. In the state-of-the-art scenario, energy demand in buildings increases from 103 EJ in 1990 to 171 EJ in 2020, at a rate of 1.7% per year. Average annual growth is 0.8% for ICs, 2.7% for EITs, and 2.8% for developing countries. Overall, 41% of energy growth occurs in the EITs, 36% in developing countries, and 23% in the ICs. In the ecologically driven/advanced technology scenario, world energy demand in buildings grows at a rate of 1.0% per year, from 103 EJ in 1990 to 140 EJ in 2020. Annual growth rates are 0.4% for ICs, 1.7% for EITs, and 1.8% for developing countries. These growth rates lead to an increase in the proportion of world energy use in buildings from 18.5% in 1990 to 23.5% in 2020 in developing countries. The share in the ICs drops from 59% in 1990 to 49% in 2020.

Table 2.11 Estimated energy consumption in buildings for three scenarios for the year 2020 (in EJ).

		Business-as-Usual		**State-of-the-Art**		**Ecologically Driven/Advanced Technology**	
Sector/ Region	Energy 1990	Energy 2020	Growth (%/yr)	Energy 2020	Growth (%/yr)	Energy 2020	Growth (%/yr)
Residential							
ICs	36.5	43.7	0.6	41.8	0.5	38.8	0.2
EITs	15.0	42.3	3.5	31.6	2.5	23.5	1.5
DCs	15.0	43.2	3.6	32.3	2.6	24.8	1.7
Total	66.5	129.2	2.2	105.7	1.6	87.1	0.9
Commercial							
ICs	24.5	38.4	1.5	35.1	1.2	30.3	0.7
EITs	7.9	25.7	4.0	19.2	3.0	14.3	2.0
DCs	4.2	14.4	4.2	11.1	3.3	8.1	2.2
Total	36.6	78.5	2.6	65.4	2.0	52.7	1.2
TOTAL	103.2	207.6	2.4	171.1	1.7	139.8	1.0

2.4 Transport

2.4.1 Introduction

Energy use in the transport sector is linked to very complex environmental and societal problems, including air pollution, lost productivity due to traffic congestion, death and disabilities due to accidents, water pollution caused by spilled petroleum, and global warming [Sperling,1995; WEC,1995b; MacKenzie,1990]. Since 1971, global transport energy use has grown at a rate faster than total world primary energy use and has nearly doubled, jumping from 37 EJ to 63 EJ in 1992 (see Figure 2.5). The rate of growth in consumption for developing countries was extremely rapid over this time period (4.7%) while growth in industrialized countries and economies in transition was more moderate (2.1% and 2.0%, respectively) [WEC,1995a].

Analyses of transport energy are typically divided between passenger and freight transport, each of which include several modes, such as automobile, truck, rail, ship, or air. Road transport, both by passenger car and commercial trucks, accounts for the vast majority of total energy use (73%), followed by air (12%), rail (6%), and other modes.

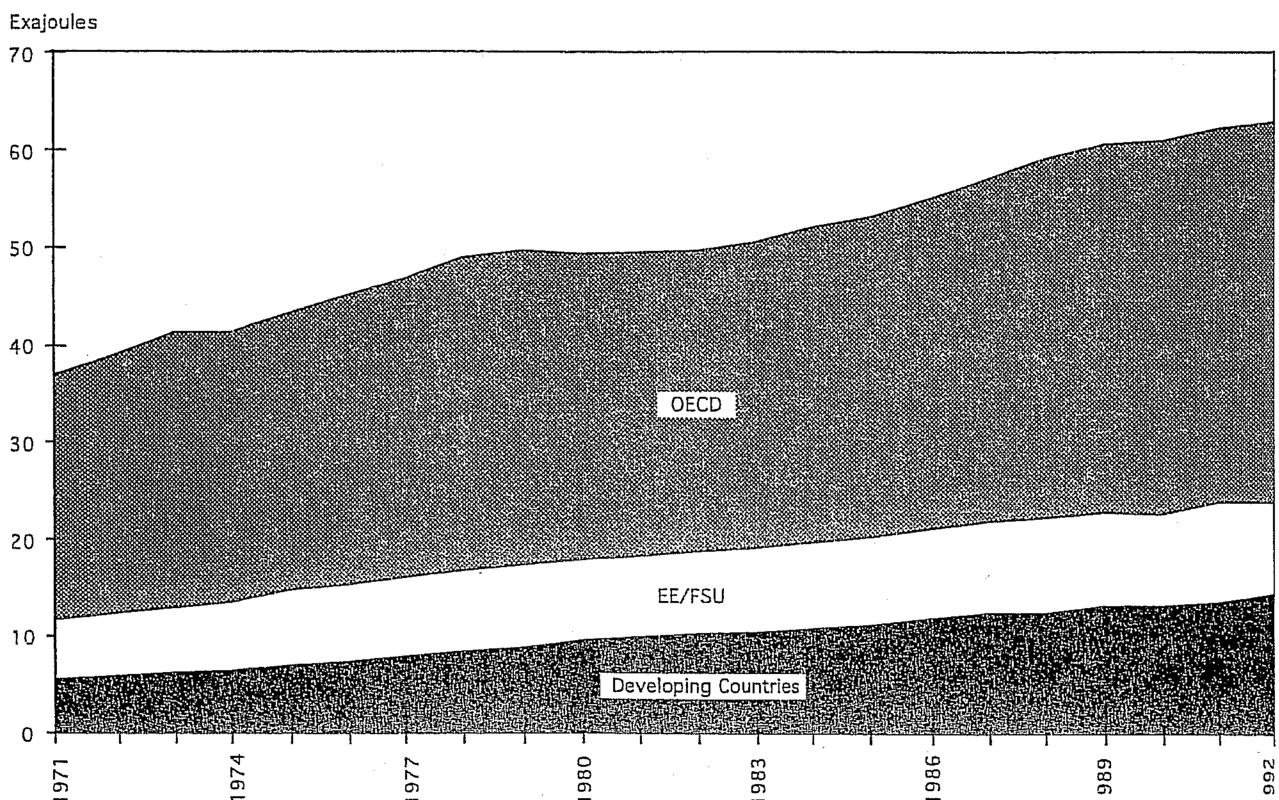

Figure 2.5 Energy consumption for transport between 1971 and 1992 for three regions.

Industrialized countries. ICs dominate transport energy use, accounting for nearly two-thirds (39 EJ) of total world energy consumption in 1992 [WEC,1995a]. Over the past two decades there has been a steady increase in the number of kilometres driven annually to transport both freight and passengers in ICs. Most of the additional activity has occurred on roads, resulting in a 2.4% annual growth in energy use for this mode which is higher than the growth rate for IC transport overall [IEA,1995a]. The share of rail for inland surface transport has declined and energy use for this mode since 1970 has been flat. Energy use for air travel has grown at rates similar to road over this period.

Developing countries. Energy use for transport in DCs has almost tripled since 1971, growing from 9 EJ to 14 EJ in 1992 [WEC,1995a]. Rapid economic growth has been accompanied by increased demand for personal mobility and increased truck-freight activity, resulting in a growth in road energy consumption averaging 6% annually. The share of energy use from road transport has increased to match IC levels (80%), while the share of rail has declined to about 8% of total energy use. Asia has shown the fastest growth in energy consumption for transportation, and accounts for about half the total transport energy use, followed by Latin America and Africa. The issue of the growth and demand for transport infrastructure is particularly salient for developing countries. The shift from labour-intensive to service-oriented economies has led to both increasing passenger transport and road freight transport intensities, reflecting increased economic activity and increased demand for personal mobility [Sathaye and Meyers,1991; WEC,1995b; IEA,1995a] and may even be expected to be higher in the future, depending on increasing income levels. Car ownership in Bangkok, for example, increased from 49.7 cars per 1000 persons in 1970 to 108.3 cars per 1000 persons in 1986, an average annual increase of 5%. Similar dramatic increases have occurred other Asian countries as well [Sathaye et al.,1994; Sathaye and Walsh,1991; IEA,1995a].

Economies in Transition. Relative to the ICs, transport energy use in EITs has been low, growing at about 2.0% annually from about 5 to 6 EJ in 1971 to about 8 to 9 EJ in 1992 [WEC,1995a; IEA,1995a]. Given historical restrictions on car ownership and the development of a vast railway network, rail has accounted for a large share of freight transport and about a quarter of total energy use. The more recent transformation of the economies in the EITs has resulted in increasing demand for road freight as well as a dramatic rise in the ownership and use of passenger vehicles [WEC,1995b]. As the economies in this region continue to transform, modal shares are becoming more heavily weighted to road transport.

2.4.2 Technical Potentials

Transport energy use can be reduced by improving the efficiency of transportation technology (e.g. improving automobile fuel economy), shifting to less energy-intensive transport modes to achieve the same or similar transport service (e.g. substitution from passenger cars to mass transit), changing the mix of fuels used in the transportation system, and improving the quality of the transportation infrastructure (roads, railways). Table 2.12 lists selected energy-efficient technologies and practices for road vehicles (passenger cars, light trucks, heavy trucks), and aircraft.

Table 2.12 Summary of selected energy-efficient technologies and practices for transport. [De Beer, et al.,1995; DeCicco and Ross,1994b; Greene,1995; Ross,1989; OTA,1994; UN,1993].

Mode	Technology/Practice
Road Vehicles	*Improve engine efficiency*: variable valve control, lean burn, increasing compression ratio, friction reduction, overhead camshaft, multipoint fuel injection, four valves per cylinder, high torque/low rpm engines (heavy trucks), electronic truck engine control, temperature controlled fan clutches (trucks), thermostatic radiator shutters (trucks), diesel engines, adiabatic diesel engines (advanced technology), fuel cell vehicles (advanced technology) *Improve transmission efficiency*: five speed transmission, continuously variable transmission, torque converter lockup, optimized transmission control, optimized manual transmission, drive train improvements (cars and trucks) *Reduce load and tractive forces*: lower rolling resistance tires, aerodynamic improvements, weight reduction, accessory improvements, lubricant improvements *System improvements*: Intelligent highway vehicle systems (IHVS), routing and operations optimization (trucks), reduced backhauls (trucks)
Railways	Improved handling during start-up and braking, use brake energy for space heating, flywheel energy storage, better energy conversion technology (choppers), reduce air drag (improved aerodynamics, reduced weight)
Aircraft	*Improve propulsion technology*: increase bypass ratio through improved engine technology, propfan technology *Improve aerodynamics*: increase aspect ratio, laminar flow control, airfoil development, turbulence control, induced dragweight reduction: lightweight materials

Table 2.13 presents an overview of selected studies regarding the technical potential for energy efficiency improvements in the transport sector. These studies show potential savings ranging between 5 and 55% depending upon the mode and study assumptions. Economic potentials are generally lower (see Chapter 4).

Equipment efficiency. For nearly all modes of transport, substantial opportunities exist to improve transportation equipment. Measures that reduce energy use in conventional automobiles include improved engine technologies, improving the transmission, and reducing the load on the vehicle [DeCicco and Ross,1994a; 1994b]. Aircraft efficiency improvements also center around similar measures designed to improve propulsion efficiency, reduce aerodynamic drag, and reduce airframe and engine weight [Greene, 1995]. Equipment improvement increased fuel efficiency in truck, car, and air fleets by 1-3% per year in OECD countries [Schipper and Meyers, 1992; Greene,1995; IEA,1991]. In road vehicles, for example, fleet fuel efficiencies in the U.S. dropped significantly from 17 liters/100km in 1970 to 10 liters/100km in 1992, but new car fuel efficiencies remained stagnant since the late 1980s [Geller and Nadel,1994]. Similar trends have taken place in Europe [Schipper,1995a; WEC,1995b; Ross,1989]. Part of the reason for stagnation in fuel efficiency has been the increased use of larger, luxury vehicles that have raised overall vehicle weight [Schipper,1995b; IEA,1995a], and developments towards increased power, rather than fuel economy.

Table 2.13 Technical potential for energy efficiency improvement in transport.

Mode	Potential	Country/Region
Passenger Cars	10-50%	World [1]
	15-25%	U.S.A [2]
	18-50%	U.S.A [3]
	40-80%	U.S.A [4]
	15-50%	OECD Countries [5]
	29-55%	U.S.A [6]
Light Trucks	13-22%	U.S.A [2]
Heavy Trucks	10-30%	World [1]
	12-51%	U.S.A [6]
	64-74%	U.S.A [7]
	5-33%	OECD Countries [5]
Trains	10-33%	World [1]
Aircraft	26-90%	World [8]
	16-34%	OECD Countries [5]

Notes:

1. WEC (1995b). Estimates represent average fuel economy improvements between 1995 and 2010 for 8 world regions.
2. National Research Council (1992). Represents technically achievable fuel economy levels in 2006 for the U.S. fleet. Percentage improvements based on comparison from 1991 EPA average fleet levels of fuel economy. For passenger cars range represents estimates for subcompact, compact, midsize, and large vehicles. For light trucks range represents estimates for pickup, small van, small utility, and large van vehicles.
3. OTA (1995). U.S. fuel economy improvements 1995-2005 for a mid-sized car. Range represents business-as-usual versus a lightweight body material (first generation aluminium).
4. DeCicco and Ross (1994). Based on comparison to new car fleet average fuel economy in the U.S. in 1990 of 8.5 l/100km.
5. Schipper and Meyers (1992). OECD fuel economy improvements 1985-2010. Range represents difference between a business-as-usual scenario and a vigorous energy efficiency scenario.
6. Alliance to Save Energy et al. (1992). Fuel economy projections 1990-2010 for the U.S. fleet. Range based on four scenarios: Reference, Market, Environmental, Climate Stabilization.
7. Sachs et al. (1992). Fuel economy improvements for heavy trucks only 1992-2000 based on improvements from a 1982 baseline of 45.3 l/100km Range reflects best available technology measures that are implemented immediately versus improvement in fuel economy of an average fleet vehicle in 2000.
8. Greene (1995). World estimates of passenger-miles/gallon between 1992 and 2015. Projections based on estimates of potential technology improvements compared to current average technology.

Fuel intensities in developing countries are often much higher than ICs, and therefore hold even greater potential for improvement. In China, for example, recent estimates of fuel intensities for diesel and gasoline trucks in 1991 were 36 l/100km and 37 l/100km respectively, or 25% higher than intensities in ICs [He et al., 1994; O'Rourke and Lawrence,1995]. Estimates of fuel economy for passenger cars in China, Mexico, and India are 10-50% higher than the U.S and Japan [IEA,1995a]. These figures are also influenced by poor roads and infrastructure (see below) and by poor maintenance, partly due to the wide variety and age of cars used.

Along with improvements in current technology, there are a number of advanced technologies, especially in the automotive area. A recent study of advanced automotive technologies noted that technical efficiency improvements from today's automotive efficiency of 8.5 liters/100km to 4.7 l/100km in 2015 is possible without a radical shift in vehicle drivetrains. If drivetrain changes are included, even greater efficiencies can be achieved. For most advanced technologies currently being developed, such as electric vehicles, hybrid electric, and fuel cell vehicles, cost remains a significant factor to ultimate commercialization. To hasten commercialization, state governments in California and various northeastern states are pressing for early marketing of electric vehicles [OTA,1995]. The demonstration and introduction of these technologies in vehicles with high capital costs, (e.g. buses), may accelerate technology diffusion for personal transportion. Electric vehicles have also been studied as an option in DCs, i.e. South Africa.

Modal shift. Significant reductions in energy use can be achieved by encouraging shifts to less energy-intensive modes of transport. Table 2.14 provides estimates of energy intensities for different modes. Strong variations in intensities exist for various modes. Shifting commuting from passenger car to bus can result in a relative intensity drop of 200%. However, increasing the load factor (i.e. the number of passengers travelling) of the automobile through carpooling could have a similar effect. One study of the US estimated that 12% of intercity truck-kilometres could shift to rail for the movement of goods, an important shift given the fact that road transport is four times as energy intensive as rail [Alliance to Save Energy,1992; O'Rourke and Lawrence,1995]. However, in ICs, freight transport has become more, not less energy-intensive over the past two decades since increasing shares of tonnage are now carried by truck and less by rail, and freight loads in a service-based economy are often higher value-added and lighter weight [Schipper,1996]. Non-motorized modes of transport can also play an important role in the transport mix. It was estimated that bicycling and walking accounted for 47% of total trips in the Netherlands compared to only 3 to 12% in the US [OTA,1994; Gordon,1991].

Fuel mix. The current transportation system depends nearly completely on petroleum products as a fuel source. However, energy security and environmental concerns have driven countries to explore and implement the use of alternative fuels within the transportation fuel mix, e.g. natural gas, methanol, ethanol, electricity, hydrogen or bio-diesel. Perhaps the most well-known case of a massive shift to an alternative fuel is the alcohol-fuel program in Brazil beginning in 1975 [Jacy de Sourza Mendona,1991]. A shift in fuel mix, however, does not necessarily affect fuel efficiency.

By using conversion technologies adapted to the fuel characteristics, e.g. fuel cells, the life-cycle costs can potentially be lower [Williams,1994]. While some fuels are attractive near-term substitutes for diesel and gasoline given their potential to reduce emissions and improve fuel economy, the large infrastructure and technology development costs associated with their full introduction into the marketplace make it difficult for these fuels to compete without significant policy intervention. Introduction in specific markets, e.g. mass transit, may accelerate the development of these technologies and provide the incentive for infrastructural changes.

Table 2.14 Energy intensity for transportation by mode in 1992.

Mode		Energy Intensity (MJ/Pass-km)		
Passenger Transport [1]		U.S.A.	Europe	Japan
	Road (Car)	2.6	1.7	2.7
	Road (Bus)	0.9	0.7	0.7
	Rail	2.1	0.5	0.4
	Air	2.6	3.0	2.3
Freight Transport [2]		Energy Intensity (MJ/Tonne-km)		
		North America	ICs Europe	ICs Pacific
	Road (Truck)	2.5	4.0	5.0
	Rail	0.3	0.4	0.4
	Air Freight	20.0	16.0	16.0

Notes.
1. Schipper (1995). Estimates for Europe based on Italy, Germany, France, and United Kingdom.
2. WEC (1995b).

Improving transport infrastructure. Transport infrastructure improvements can occur through increasing availability or supply of infrastructure or by reducing demand. In road systems supply improvements include such measures as increasing lanes or highways, or expanding a light rail-network. Given the high costs of supply expansion, planners are beginning to examine methods to reduce the demand by transport vehicles, or to better optimize the use of existing infrastructure. Actions that can increase the load factor for any particular mode are also desirable, such as the construction of High Occupancy Vehicle lanes (HOVs) in passenger transport. Numerous technological innovations are possible that can improve traffic flow within current systems. Smart vehicle technology, also know as Intelligent Highway Vehicle Systems (IHVS), will allow drivers to reach their destination on the least congested route. Improved signalling and communication technologies can speed traffic flow and notify drivers of parking availability thereby reducing idling time. Finally, telecommuting has some potential to reduce the number of work-related trips, although it is not clear yet whether telecommuting can reduce overall vehicle miles travelled [Niles,1994; Handy and Mokhtarian, 1993].

Policies that encourage large shifts to public transit systems in densely populated areas such as Singapore, Curitiba, and Manilla have been shown to reduce overall energy demand [Sathaye et al.,1994; Birk and Bleviss,1991]. Land use planning is an important tool to encourage shifts to mass transit. In Curitaba, Brazil, the city's bus line accounts for 70% of total transport, and per-capita energy use is 30% lower than comparable Brazilian cities [Birk and Zegras,1993]. This example and other studies indicate that land-use planning and transportation system policies could reduce energy consumption in other developing countries.

2.4.3 Scenarios of Future Energy Use in Transportation

Scenarios of energy use in transportation need to account for technical efficiency improvements to the transportation stock as well as the rate of growth of energy use within the various transport modes. The activity growth is derived from [WEC,1995b]. Under the business-as-usual scenario, global transport energy use grows at a rate of 3.3% per year, increasing from 61 EJ in 1990 to 137 EJ in 2020, with the largest increase taking place in developing countries (45 EJ). Growth in energy use is expected to be higher than recent growth trends in both the EITs and DCs. Growth in ICs transport energy use is expected to be lower than historical trends. In the state-of-the-art scenario energy demand in the transport sector increases from 61 EJ in 1990 to 108 EJ in 2020, at a rate of 2.3% per year. Energy use grows less rapidly due to the more rapid penetration of technical efficiency improvements in most travel modes, particularly in road transport. In the ecologically driven/advanced technology scenario, energy demand grows at a rate of 1.2% per year, from 61 EJ in 1990 to 82 EJ in 2020. This scenario assumes policies that significantly reduce transport demand, encourage greater use of less energy-intensive transport modes, and use of efficient technologies.

Table 2.15 Future energy consumption (in EJ) in transport for three scenarios until the year 2020.

		Business-as-Usual		**State-of-the-Art**		**Ecologically Driven/Advanced Technology**	
Sector/ Region	Energy 1990	Energy 2020	Growth (%/yr)	Energy 2020	Growth (%/yr)	Energy 2020	Growth (%/yr)
Transport							
ICs	38.0	57.0	1.4	48.5	1.0	33.5	-0.5
EITs	10.0	22.0	2.7	18.0	2.4	15.0	1.6
DCs	13.0	58.0	5.1	41.5	4.8	33.0	3.8
Total	61.0	137.0	3.3	108.0	2.3	81.5	1.2

3. Assessment of Material Efficiency Improvement

3.1 Introduction

Historically, industry has been an open system, transforming resources to products or services that are eventually discarded after use by society. This system is non-sustainable as it consumes non-regenerative resources and produces large quantities of waste. The environmental problems associated with each step in the production and consumption processes have led to a re-evaluation of the way the economy works. 'Industrial ecology' studies industrial systems in analogy with natural processes [Socolow et al.,1994; Ayres and Simonis,1994]. Although the biological system leaves some wastes, it is a self-sustaining system with solar energy being the only external input. 'Industrial ecology' looks for changes in policy and practice that will push the system in sustainable directions [Frosch,1994].

Industry consumes a large part of global primary energy demand (43% in 1990), of which over 50% is used for production of a limited number of basic materials (see chapter 2). The energy intensities of materials differ significantly, as shown in table 3.1. Decreased use of (primary) materials to manufacture products or perform services will reduce energy use. Material efficiency improvement is defined as reducing the amount of (primary) material needed to fulfill a specific function or service. To avoid doublecounting, the use of materials to improve energy conversion processes is viewed as energy efficiency improvement and is not treated in this chapter. Our main focus is the possibilities to reduce the current consumption levels of materials by materials efficiency improvement. Although most of the research we summarize is from industrialized countries, we will apply the findings to developing countries as well.

Table 3.1 Gross energy requirements (GER) of a number of primary materials. The GER describes the energy consumption needed to produce the material or product starting with the extraction of resources. The GERs are only indicative, as large differences in energy efficiency occur in production (see chapter 2). Derived from [Worrell et al.,1994a].

Material	GER (GJ/tonne)	Remarks
Steel	19.9	Primary steel slabs
	25.2	Cold rolled steel
Aluminium	187.1	Ingots
Ammonia	34.0	Natural gas feedstock
Ethylene	60.6	Naphtha feedstock (incl. feedstocks)
Paper	12.0	Board
	39.0	Printing paper (incl. feedstocks)
Cement	2.5	Blast furnace slag cement
	4.0	Portland cement
Glass	8.1	Container glass

Reducing material inputs into production can be achieved through more efficient use of materials and closing material chains. Good housekeeping, material efficient product design, material substitution or use of materials with improved properties[7], product and material recycling, and decreasing inputs of primary materials all improve material efficiency. Similarly, practices that promote dissipative (non-recoverable) use of materials should be reduced. Reducing material intensity may also have effects on other actors in the material chain, e.g. energy savings in transport, and subsequently on material demand for these services. Eventually, such reductions will reduce the society's demand, and the materials 'on the menu', leading to a structural change within the economy to a lower share of energy/material intensive services. Structural change is an important driver for reduction of energy consumption [Schipper and Meyers,1992]. Structural change towards a more service-oriented society as a result of long term economic development within societies (inter-sectoral change) will reduce energy intensity. Intra-sectoral changes may occur due to changes in inputs and outputs of industrial sectors, e.g. increased use of secondary materials through improved recycling. Developing countries have high material intensities due to the construction of infrastructure and growing demand. In some areas, demand of materials is growing as fast as or faster than the economy. This demand will saturate at stages further along the development, leading to an uncoupling of materials production growth and economic development [see Williams et al.,1987].

3.2 Historical Developments of Materials Use

Material consumption is still increasing. This growth is apparent for 'classic' materials (e.g. cement, steel) and for the 'new' materials (e.g. plastics, aluminium). Studies of material consumption in industrialized countries have shown that the consumption (expressed as apparent consumption per capita or unit GDP[8]) increases in the initial development of society to a maximum, and eventually saturates or even declines [Williams et al.,1987]. Trends in materials use in industrialized counties show saturation on a per capita basis. Expressed as function of unit GDP, material intensity declines after reaching a maximum [Williams et al.,1987] (see also figure 3.1). The initial increase is caused by large investments required in building an industrial infrastructure. In later stages material substitution and competition between materials as well as a shift to a more service-oriented economy, decrease the material intensity of societies [Williams et al.,1987; Bernardini and Galli,1993]. For example the substitution of classical steels by aluminium in transport applications led to the development of high strength steels that can compete

7 Substituting less energy-intensive materials by more energy intensive, e.g. steel by plastics, might still be energetically beneficial, if the specific material consumption for the same product or service decreases.

8 International statistical data give the apparent consumption of materials, i.e. the intermediate consumption of materials in industry. Due to increasing import and export streams of products (containing the materials) the figures represent the consumption by the economic production sectors, rather than the end-use of the society. The first detailed analyses of end-use in some countries are available but not yet as time series. The availability and comparability of GDP data is often difficult, as we know from energy intensity analyses, see e.g. [Schipper and Meyers,1992; Martin et al.,1995]. Comparisons of the material intensity, expressed as material use per unit GDP, should be interpreted carefully.

with aluminium (e.g. the ULSAB project).[9] Because of the improved properties less material is needed to fulfill the service, leading to declining material intensities. Recycling also appears to increase with development [Bernardini and Galli,1993], as can be seen from the increasing post-consumer recycling rates in the industrialized world. The above-mentioned development curves seem not only valid for construction materials but also for other commodities like food [Bernardini and Galli,1993], fertilizers [Williams et al.,1987] and pesticides. In addition, Bernardini and Galli (1993) suggested that the maximum intensity declines if reached later in time by a given economy or society. However, most analyses have been performed only for industrialized countries. The need for further analysis is stressed by the current situation in rapidly-industrializing countries like South Korea, that have a very high per capita apparent consumption of steel which is used in large exporting industries like car manufacture and ship building.[10]

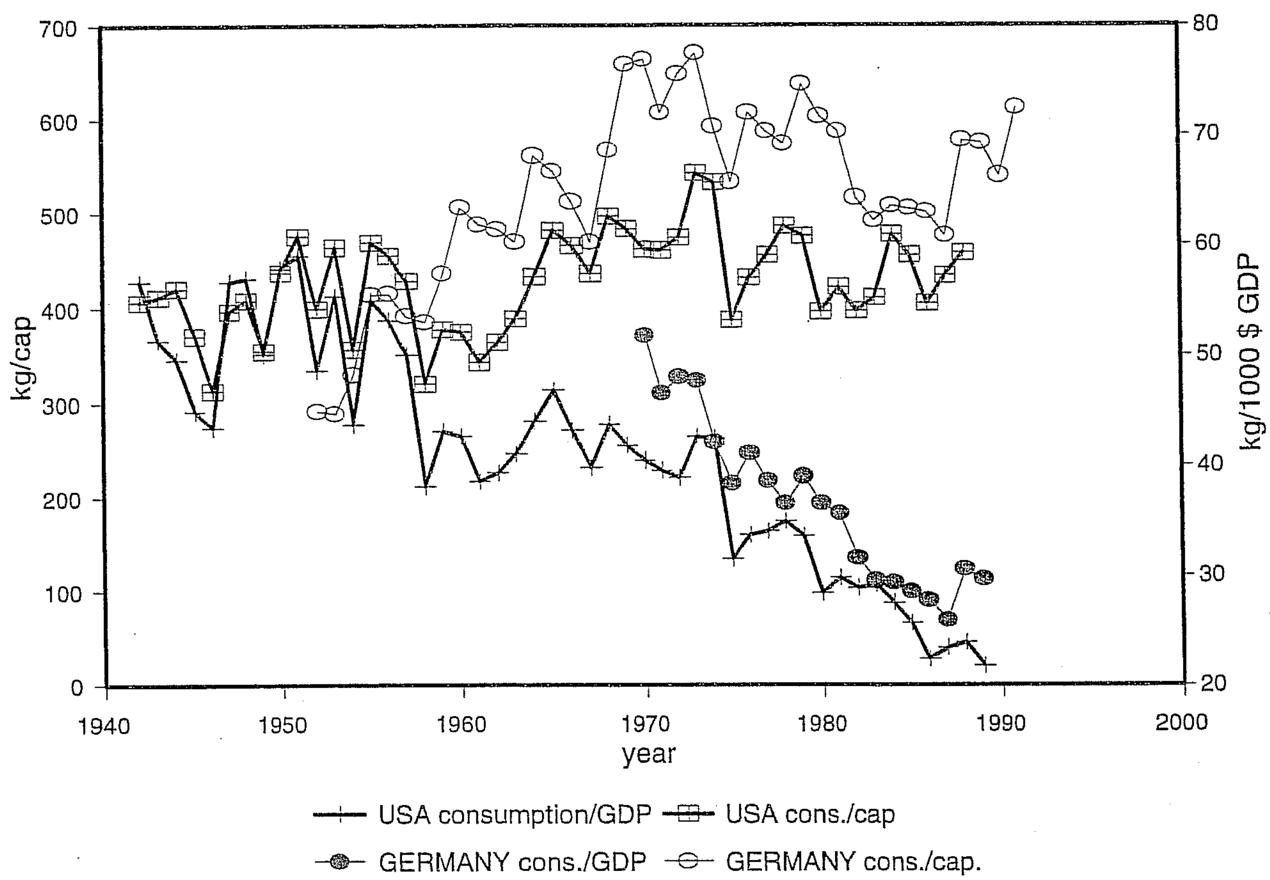

Figure 3.1. Steel consumption in the U.S.A. and Germany for the period 1940-1990. The development of the apparent consumption is depicted as function of GDP and per capita.

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9 In the ULSAB (Ultra Light Steel Auto Body) project, steel and car manufactures develop a car with strongly reduced weight using new manufacturing technologies and meet all design requirements.

10 This case shows that the available statistics are not yet suited to prove that countries developing later in time will reach a lower saturation level, as stated by Bernardini and Galli (1993).

Although the use of all materials in developing countries will certainly grow, the likely per capita consumption may not be as high as in the industrialized countries. What the saturation level, will be, depends on many factors, including technology transfer but also infra-structural (including economic structure) policy choices. Macro-economically some of these trends can already be observed. For example, the rapidly developing East-Asian countries, already show a growing economic importance of the services sector.

3.3 Material Efficiency Improvement Options

In this section we discuss the options to improve material efficiency for some bulk materials. At several stages in the material life-cycle, intervention can increase the material efficiency over the total cycle. We define several measures, depicted in figure 3.2:

- *Good housekeeping*. Reduction of material consumption, without changing the function or design, by reduction of the product consumption or improved use of the product by the user or consumer, i.e. reducing the material intensity of the performed service. Generally no costs or only low costs are involved. Good housekeeping includes reduction of material losses in production processes.
- *Material-efficient product design*. Re-designing the product to a lower material intensity, by reducing the amount of material needed to manufacture a functional unit of the product, by increasing the lifetime of the product or by improving its repairability. Several concepts are introduced to measure the environmental impact of a product or service, see e.g. Schmidt-Bleek (1994), or to improve a product, using life cycle analysis (LCA), see Fava et al. (1991) and Keoleian and Menery (1993).
- *Material substitution*. Replacement of the original material by another material with a higher material efficiency, or by a material with a lower GER, decreases the energy demand of the product-cycle.
- *Product reuse*. The renewed use of a product, without changing the physical appearance during recycling. The product is collected, transported, cleaned and used again. Often the product has to be redesigned to permit product reuse.
- *Material recycling*. Recycling produces secondary material, by mechanical, chemical or other recycling technologies. The expression is used in this study if the material is used for similar functions with comparable material qualities. Recycling of materials is generally less energy intensive and may lead to considerable energy savings depending on the material, see e.g. Elliott (1994). Note that recycling costs, being a labour-intensive activity, strongly depend on the labour costs. In developing countries a large informal recycling sector seems to exist, leading to low recycling costs.[11] High labour costs in the industrialized countries are often

In many developing countries high valued materials (e.g. metals) are collected by an informal sector (scavenging), leading to relative high recovery rates [Yhdego,1995], but social conditions are generally very poor. Many industries in developing countries rely on high inputs of secondary materials, e.g. the Indian steel industries are large importers of scrap from the industrialized countries, importing scrap equivalent to 15% of the total steel production in 1990 [IISI,1992].

prohibitive for recycling schemes, especially for low cost primary materials and reduced qualities of secondary materials, although more recyclable material is available.

- *Quality cascading*. The use of secondary material for a function with lower quality demands, or 'open loop' recycling, see Sirkin and Ten Houten (1994) for a full discussion.

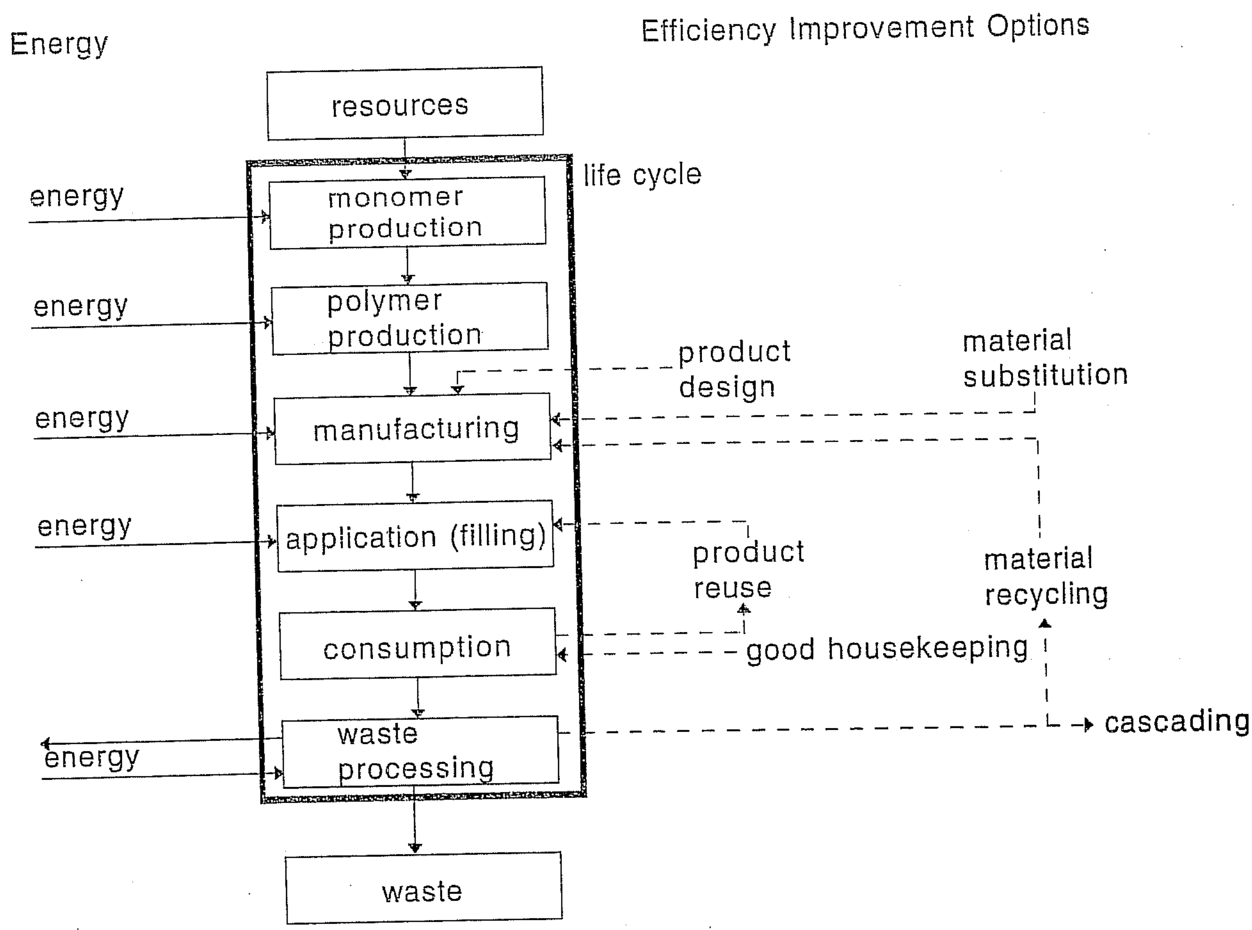

Figure 3.2. The life-cycle of materials. The standard life-cycle is presented within the box. The efficiency improvement measures that can be applied are depicted outside the box. The product is used to perform a service. This is part of the consumption phase. Good housekeeping will reduce the material needs.

Several options are available with respect to each measure listed above. For each measure the reduction potential (volume and energy demand), costs, and implementation barriers should be investigated to assess the best policy strategies. The energy consumption of the new life-cycle should be corrected for the energy consumption of the activities that will be added by implementing the measure. The associated primary energy savings can then be calculated. Below we will discuss the possibilities and potentials for some major materials with regard to energy use in the production (see chapter 2), followed by a discussion of some general studies.

Metals: Steel. Steel consumption has been stable or decreasing in the past decade in the industrialized world and recently in Eastern Europe due to the economic downfall. The strongest growth of steel demand can currently be found in Asia [IISI,1992]. The steel industry in China recently showed an annual growth of 8%, and will probably be the world's largest within a decade.

Recycling of metals has a long tradition, and established national and worldwide industries collect and process scraps. Recycling of scrap is an integral part of primary steel production, but scrap can also be recycled in separate plants. Currently 40% of global crude steel is produced from scrap, while the share of the electric arc furnace (which mainly uses scrap) increased from 24% in 1982 to 29% in 1991 [IISI,1992], with the strongest growth in the ICs and Asia. Steel recycling is a well established business, and international scrap trade is increasing. Still, recovery of scrap could increase, especially from municipal solid wastes. The material losses in steel manufacture can be reduced through the introduction of continuous casting and processing. The casting material losses can be reduced to 2-3%, instead of 8-12% for ingots, saving energy (as most of the scrap is recycled internally). Sealed convertors in primary steel making can reduce the material losses in steelmaking by 1% [WEC,1995a]. The development of new high strength steels has led to reduction of the amount of steel required for a function. The average iron content of cars[12] in the US decreased by 31% between 1975 and 1985 (total car weight by 16%) [Williams et al.,1987]. This trend is expected to continue with projects like ULSAB (see above) reducing the car body structure weight considerably. Improved corrosion protection can increase the life-time of constructions considerably. A complication is that this might lead to contamination of secondary steel, e.g. by zinc, that might make recycling in the long run more difficult (although in primary steelmaking the zinc is removed and might be recovered from the sludges/slags).

Cement & Concrete. Cement is made by mixing clinker (burnt limestone) with additives, and is used to produce concrete. Cement is a classic construction material, showing high growth rates in the rapidly developing economies. Cement consumption in industrialized countries and Eastern Europe has reached a saturation level of approximately 450 kg/ca in 1990 [WEC,1995a] (with higher figures for individual countries) after previously higher consumption levels [Williams et al.,1987]. Average consumption in developing countries is still much lower at 136 kg/ca in 1990. China, now the world's largest cement producer, had an annual consumption of 180 kg/ca in 1990 [Van der Vleuten,1994].
Cement cannot yet completely be recycled in a 'closed loop' (although chemical reclaiming[13] of cement from waste concrete is being investigated [Kojima et al.,1993]). Ground waste concrete is used as filler in many applications (e.g. in some concretes, road construction), reducing the

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12 Note that the fuel savings in transport due to reduced weight are larger than the energy savings due to reduced material manufacture.

13 Chemical recovery is a new technology, and not discussed much in the literature. The energy gains remain unclear, due to the relative low energy intensity of cement.

quality of the original cement, thereby limiting application.[14] Management of the cement production cycle should therefore aim at the improvement of the properties of cement (e.g. high strength cements [Goldemberg et al.,1988]), reducing the material needs, development of alternative lower material-intensive construction techniques, reduction of the energy intensity of cement by energy efficiency improvement (see chapter 2) or increased use of blended cements (e.g. use of alternative pozzolanic materials like blast furnace slags, fly-ash, etc.). Large differences in application of blended cement exist between individual countries (due to resource availability and existing product standards), and large potentials exist for various countries [Worrell et al.,1995c]. Reducing clinker needs for cement production will also decrease the emission of mineral CO_2 from burning limestone, accounting for over 1% of global CO_2 emissions.

Pulp & Paper. Produced in over 80 countries, paper is a commodity used for a wide variety of purposes in many different qualities and grades. Global paper consumption doubled between 1975 and 1991, and is expected to increase by 80% by 2010. Large growth is expected in Asia, due to the increasing economic development in the region. The principal markets are packaging (40%), printing and writing (30%) and newsprint (13%) [IIED,1995]. Figure 3.3 gives an overview of the specific 1989 printing/writing paper consumption in various countries.

The paper products stream is an example of successful recycling schemes, although with variations on a national basis. Current national policies in the field of paper are directed towards increasing the recycling rate of paper fibres, through mandating product demands for the recycled fibre content. Most of these regulations have been proposed for newsprint paper [IIED,1995] requiring recycled fibre contents of 40-60%. An US study has suggested that increased recycled content for a wide range of paper types is appropriate [RAC,1992]. Since quality of the fibre determines the recyclability, paper manufacture is a good example where quality cascading [Sirkin and Ten Houten,1994] is needed for an optimal allocation of recycled fibres. The waste paper recovery rate is increasing worldwide, and is estimated at 38% in 1992, with the highest rates in Austria (71%) and The Netherlands (63%) [Byström and Lönnstedt,1995]. Many ICs have set targets to reduce the waste volumes. More efficient use of materials, or reducing consumption, currently receives limited attention in policy. In The Netherlands the so-called *Packaging Covenant* aims at reducing the amount of packaging materials (not only paper) used in 2000 to a level of 10% below the 1986 use. Only a limited number of studies have looked at the possibilities of reducing the use of paper. One German study [Greenpeace,1991] estimated a possible reduction of paper consumption up to 50% for various paper products in Germany. Examples from industry [IIED,1995] show that reductions of 20-50% of packaging materials are feasible within short periods. Improved office practice (like double-sided copying) at AT&T in the USA led to 10-15% reduction of paper consumption, and considerable cost savings [IIED,1995]. Current developments like "de-copying" machines, removing the toner from the paper, may also reduce consumption of paper, although energy savings are yet difficult to assess.

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14 This re-ground cement will not replace cement, but rather fillers, e.g. sand and gravel, leading to small energy savings.

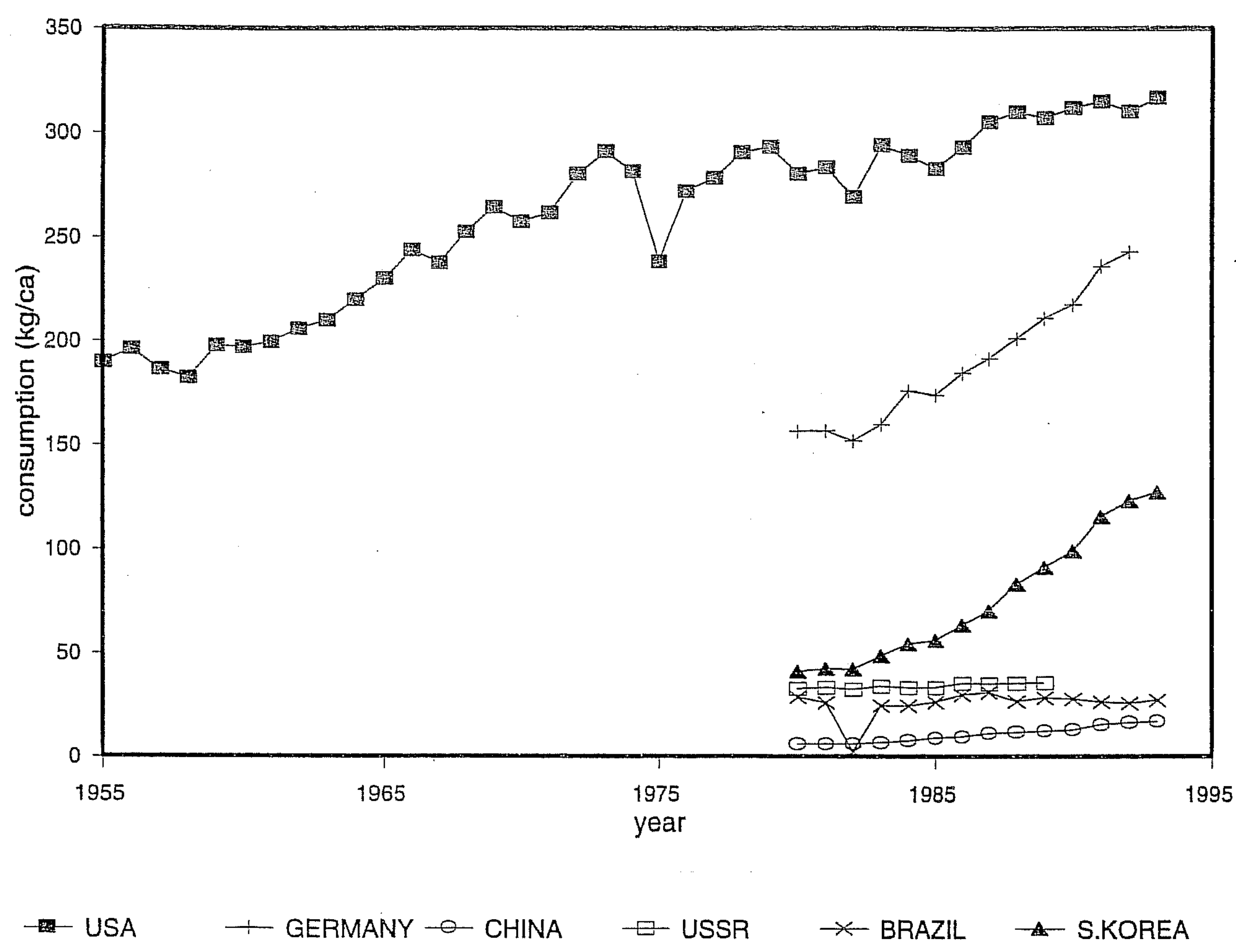

Figure 3.3 Per capita consumption of paper for selected countries (expressed as kg/capita).

Plastics. Plastics are used in a wide variety of applications showing a strong growth in industrialized and developing countries. Global consumption is estimated at 72 Mtonnes (1990), with most of the production and consumption in the USA (~40%, equal to 114 kg/ca) and Western Europe (~36%, equal to 73 kg/ca). The strongest growth of production and consumption is in Southeast Asia. Important markets are packaging (38% in Western Europe [PWMI,1992], 43% in USA [Modern Plastics,1993]) and building (33% in USA [Modern Plastics,1993]). The properties of plastics can be adapted to the demands of the service, proving them to be a versatile construction material. Plastics are used for products with a short life-time like packaging to long life-time applications such as building materials. Although energy-intensive (see table 3.1), plastics can still be a favourable material due to its tailor made properties and light weight. Efficiency improvement options can be found in every stage of the life-cycle of plastics. Development of plastics with improved properties reduces the material intensity for various applications, e.g. the use of linear low density polyethylene (LLDPE) to replace LDPE for films leads to reduced material needs [Worrell et al.,1995a], and may also lead to favourable substitution of other materials, e.g. LLDPE bags instead of paper bags. Improved product design may lead to designs with less material needs. A special example is improved design for re-use of a product, e.g. polyehtylene-terephtelate (PET) or Polycarbonate (PC) bottles for 20-100 times reuse [Worrell et al.,1995a]. Recycling of plastics is just starting, especially of post-consumer wastes. With a total post-consumer waste production of 13.6 Mtonnes (1990) in Western Europe only 7% was recycled [PWMI,1992]. Contamination and mixing is especially for plastics recycling a problem [Hegberg et al.,1993]. Effective recycling depends on ability to retain the quality of the material, although some degradation may be unavoidable (see e.g. [Mølgaard,1995]). Efficient waste collection schemes are important. New 'deep' recycling technologies are under development (selective dissolution, back-to-monomer, back-to-feedstock) which might lead to easier plastic waste collection, although the energy savings are probably very limited for back-to-feedstock technologies.

Few studies have analysed options for material efficiency improvement through the life-cycle of a material. One study that analyses the potential for material efficiency improvement for plastic packaging materials in The Netherlands found a technical potential of 34±7%, resulting in net primary energy savings of 31% (Worrell et al.,1995a). This study also showed that product re-design and substitution have energy savings equal to recycling and these savings are probably more cost-effective. Other studies investigate only one option like recycling [PWMI,1992; Ehrig,1992; Menges et al.,1992] or investigate the alternatives for a specific product. It is important to note that these studies point out that options do exist, although they are difficult to translate to other applications or higher aggregation levels.

Fertilizers. We focus on nitrogenous fertilizers because they are more energy intensive and applied more intensively than other fertilizers. Application rates of fertilizers vary widely with country, crop and agricultural practice. Average applications vary from 2 kg N/ha (Africa) to 220 kg N/ha (The Netherlands) [LEI,1992]. Large regional differences in nitrogen surpluses (e.g. The Netherlands) or deficiencies (e.g. some African regions) exist. More intensive farming practices lead to increasing nitrogen inputs [Helsel,1992]. Nitrogen is used in the growing process of the crops, but lost due to leaching or evaporation. Fertilizers are a good example of materials showing a dissipative use, and where closing of substance chains is impossible. Material efficiency improvement therefore aims at mineral management, and reduction of losses in the life-cycle. It is possible to reduce these losses through a wide variety of measures: implementation of recommended fertilization levels, integrated fertilization, improved manure application, fertilizer spreader maintenance, adaptation of fertilizer spreading geometry, improved placement or row application, catch crops or biological fixation, matching soil nutrient availability to crop needs and timing of application [Worrell et al.,1995b; Helsel,1992]. A study for The Netherlands showed that in the short term the current N-fertilizer use could be cost-effectively reduced nearly 40% and without yield losses, to an average fertilization level of 128 kg-N/ha [Worrell,1995b]. Over the longer term more efficient crops could reduce the fertilizer losses in the European Union even more [WRR,1992]. A study for India showed that the average N-fertilizer consumption increased from 10 kg-N/ha (in 1968) to 67 kg/ha in 1989 [Aggarwal,1995]. Still considerable potential from

20 to 50% depending on the crops for more efficient use existed in the investigated region in India.[15]

General Assessments. The first assessments using integrated material-energy modelling have been performed. Although these studies use high aggregation levels, which make it difficult to assess the influence of the product-life-cycle characteristics, they clearly show that material efficiency improvement or life-cycle management can play an important role in reducing energy demand. Goldemberg et al. (1988) assessed the effects of changing material consumption patterns in society, building on the saturation trends in industrialized countries [Williams et al.,1987], increasing recycling and development of materials with improved properties. Despite the high aggregation level in this study it showed that stabilization of consumption level per capita and reduced needs on the long term are feasible.

The first results of a system-integrated study for The Netherlands were translated to Western-Europe [Okken and Gielen,1994] and showed that materials life-cycle management of plastics could reduce the total CO_2 emissions of The Netherlands by 2%/year in the long term, despite strong growth of the plastics consumption. It also showed that under restricted CO_2 emission levels, material substitution and material efficiency improvement play an important role in the long term. First assessments showed an increased consumption of aluminium (for transport) and wood (in construction), while cement consumption decreased. Steel and plastic consumption remained constant relative to a baseline scenario [Okken and Gielen,1994]. The assessments also showed that integrated material and energy policies reduce the costs of CO_2 emission reduction.

In a large number of countries environmental life cycle assessments (LCA) [see e.g. Fava et al. (1991)] of individual products have been executed. Despite the uncertainties of using the LCA-tool (see a.o. [Ayres,1995]) they are useful as a design tool. Most of the LCAs show potential areas for product improvement. Although limited to specific products, the wide spectrum of products assessed indicates that improvements can be found in nearly all products. Experimental programmes for assessing processes as a tool to develop clean processes are developed in many countries [a.o. Schmidt-Bleek,1994] as well as disseminated internationally (e.g. EU, OECD, UNEP) [Christiansen et al.,1995; Yakowitz and Hanmer,1993]. These programmes indicated potentially large reductions in material losses and substitution of process inputs can lead to increased (material and energy) efficiency and strongly reduced waste production.

3.4 Policy Implications

The discussion of some bulk material streams above showed that possibilities do exist to reduce the demand of primary materials in industrialized countries and to reduce the growth rate of materials consumption in developing countries without limiting the development rate. Instead, such

[15] The figures of 20-50% express a reduction in total energy inputs of fertilizer and irrigation, for wheat, maize fodder and sorghum. Fertilizer use represents approximately 75% of the total energy inputs, and irrigation 6% [Aggarwal,1995].

reductions will lead to a more sustainable development path with respect to resources use and waste management, and reduce future environmental problems, as found in industrialized countries with respect to (the high costs of) hazardous waste removal and soil and water clean-up. A change in the waste composition in developing countries is already taking place, reducing the share of compostable material and increasing that of recyclable materials. The total amount of municipal solid waste (MSW) in Taiwan has more than doubled between 1980 and 1990 and now contains over 55% recyclable material [Yang,1995], while MSW in Tanzania is still primarily composed of vegetables and other compostable material [Yhdego,1995].

Although some material efficiency initiatives are under development and being implemented, significantly more efforts are needed. There exists a strong need for integration of concepts of cleaner production in other legislation [Christiansen et al.,1995]. Frosch (1994) distinguished six types of barriers to recycling listed in table 3.2, but these may also be interpreted more generally to materials policy and chain management.

Internationally, there exists a need to streamline product development practices, to overcome trade barriers, and to comply with international trade agreements. Restructuring environmental legislation is needed, especially for developing countries. Restructuring for chain management may have multiple benefits with regard to resources and energy consumption and imports, waste management and future exports of products. In turn, this will mean growing markets for clean design and production technologies [Luken and Freij,1995]. Strengthened R&D policies with respect to environmental design of products and services are needed.

Table 3.2. Barriers to implementation of material efficiency improvement as categorized by Frosch (1994).

Type	Examples
Technical	Suitability of the material for intended reuse (mixing of materials, maintenance difficult, design for re-manufacture), environmental design practices
Economical	Costs (subsidies for virgin materials, high costs of recycling due to high capital and labour costs) and cost allocation (production vs. disposal)
Information	Information for product design (eco-design), on supply and needs of secondary materials (incl. quality), for the consumer (product labelling, disposal)
Organisational	Internal organisation firms, organisation materials trade ('virgin' vs. 'secondary' traders, waste exchanges and brokerages, organisation of waste management, linking of actors), linking product developers and users (service oriented design).
Regulatory	Waste management still end-of-pipe oriented, inconsistencies between regulations (often directed to one environmental sector), virgin materials regulated differently than waste materials
Legal	Disposal favoured over selling (liability), for e.g. use of waste materials in products, or product demands (e.g. GATT, EU)

Sources: Sirkin and Ten Houten (1994), Pearce and Turner (1992), Hukkinen (1995).

Generally, priorities in material efficiency improvement can be ranked as good housekeeping, environmental product re-design, product reuse, closed-loop recycling, cascading (open-loop recycling), and eventually energy recovery. Nearly all of these steps require the re-design of products with emphasis on the product life-cycle (services performed) *and* materials, and management of material chains. Currently policies in many countries in the field of materials are not organised for the management of full material chains. Instead, they are limited to single aspects of the life-cycle, e.g. mining and resources use, waste management). Legislative initiatives in several countries are aimed at increasing the producer responsibility to include the total cycle of the product, and are generally aimed at involving the producers in waste management and recycling activities. The first programme of this kind was introduced in Germany, and other industrialized countries followed (see IIED [1995]); such programs have also been introduced in newly industrialized countries like Taiwan [Yang,1995]. The 'teething troubles' of the German system have mostly been surmounted, although a thorough evaluation (esp. with regard to waste prevention/good housekeeping) is still needed. Consumer information (voluntary or compulsory) to encourage demand for environmentally benign products is a step towards more sustainable production that is taken in many countries, e.g. eco-labelling. To maintain objectivity standardized and independent procedures are needed. Corporate and governmental procurement programmes are also established as 'market-pull' instruments, although these are not yet used widely.

Currently, policy instruments are mainly directed towards waste management. Design and development of sustainable products should be more emphasized. Design practices should be more oriented toward sustainable product development [Christiansen et al.,1995, OTA,1992b, Van Weenen,1995], which incorporates not only energy but various other environmental issues as well (e.g. use of hazardous materials). Information on material chains, products and management are still scattered, and comprehensive analyses, such as those executed in the field of energy policy, are limited. This is especially true for final use of materials in products/services, where more detailed analysis of product service/function oriented policies, and the potential for materials efficiency improvement is needed. Parts of the material cycles are well documented (e.g. resources supply, raw materials production and waste management). Improved information is needed in the transformation of industrialized countries, but is even more useful in the economic development process of developing economies to adjust to sustainable processes without the mistakes of the industrialized world with its non-sustainable reliance on high throughput of resources. Information is needed on sustainable product design and production technology (including recyclability and material recognition technology), as well as guidance of end-use services and functions.

3.5 Scenarios of Materials Use

In chapter 2 we estimated the economic growth of the industrial sectors, expressed as growth of the production volume. Reducing the consumption of materials in industrialized countries, and changing the economic developments in developing countries towards reduced material intensive development tracks will reduce the expected production volume growth. The increased production of high value-added materials and products, as well as growth of the services sector in the economy, will not lead to reduced economic growth (production value, value added).

We follow the same scenario-types as those produced for energy efficiency improvement. Increased recycling and use of waste materials was already part of the energy efficiency scenarios. Materials efficiency improvement will influence the production growth, and the total energy savings will strongly depend on the assumed energy efficiency improvement rate (see table 2.8). In the business-as-usual scenario we assume the estimated growth figures in chapter 2, as current developments in mainly industrialized countries have been taken into account in this scenario. In the state-of-the-art scenario we assume a more rapid uptake of product development strategies in industrialized countries and economies in transition, leading to reduced consumption for most materials. The effect on the material intensity of the development process in developing countries is less pronounced, as the demand for infrastructural materials will continue to grow. In the ecologically driven/advanced technology scenario we assume the implementation of a large number of measures reducing demand for materials, including product design, good housekeeping (through reduced consumption for e.g. packaging) and increased re-use of products. In this scenario the demand for materials is reduced to levels that are technically feasible in the short term. For simplicity we have assumed no changes in market shares and import/export positions relative to the business-as-usual scenario.

Table 3.3 Scenario results for material efficiency improvement for the period 1990-2020. The figures express the annual activity growth for the various materials for the various scenarios.

Sector	Region	**Business-as-usual** (%/year)	**State-of-the-art** (%/year)	**Ecologically driven/AT** (%/year)
Iron and Steel	ICs	0.7	0.4	0.0
	EITs	0.1	0.0	0.0
	DCs	4.0	4.0	3.0
Chemicals				
Ethylene	ICs	3.0	2.5	1.5
	EITs	1.5	1.5	1.0
	DCs	5.0	5.0	4.0
Ammonia	ICs	0.0	0.0	-0.1
	EITs	0.5	0.0	-0.1
	DCs	4.0	3.0	2.0
Petroleum Refining	ICs	1.0	1.0	0.5
	EITs	1.0	1.0	0.5
	DCs	3.0	3.0	1.5
Pulp and Paper	ICs	1.5	1.0	0.0
	EITs	1.5	1.0	0.5
	DCs	5.5	5.0	4.0
Cement	ICs	1.0	0.0	0.0
	EITs	1.0	0.5	0.0
	DCs	4.0	4.0	3.0

3.6 Conclusions

Materials use in society is strongly dependent on the development stage of a society, and will eventually saturate (expressed as material consumption per capita) or decline (expressed as material consumption per unit GDP). Industrialized countries currently show saturation, as the role of the services sector in the economy increases. This chapter has described that a wide range of (technical) options to further reduce material consumption, ranging from good housekeeping to product and material recycling. These measures are initially applicable to industrialized countries, but may be transferred to developing countries as well. However, as the scenarios illustrate, materials consumption will increase dramatically in those developing countries. High economic growth rates can be sustained with lower material intensities, if advanced, clean production practices are introduced in these countries ('leap frogging'). International policies aimed at clean production technologies and products are needed for developing countries.

Development of clean products is not solely aimed at reducing the energy consumption in product manufacturing, but also includes other environmental impacts. Attention for energy should be emphasized, as many emissions are coupled to the use of energy. Materials efficiency improvement is a new research field, compared to energy efficiency improvement, and current studies are often aimed at specific processes (e.g. recycling) or products (e.g. product LCAs). Knowledge in the field is still rudimentary, and an extensive research agenda in all aspects of material life cycle is merited.

4. Implementation Barriers and Policy Instruments

In the previous chapters it was shown that large technical potentials exist for energy and material efficiency improvement. Even though a large portion of these potentials is cost-effective, they are still not implemented. In this chapter we describe the barriers and reasons for this "implementation gap" (section 4.2). A wide body of literature describes policy instruments to overcome these barriers and to increase the implementation rate of energy efficient-technologies. In section 4.3 we present a systematic overview of the main instruments applied in industrialized and developing countries. Although the discussion will focus on energy efficiency (due to the existing literature and research), many of the instruments are also useful for materials efficiency implementation (see also chapter 3).

4.1 Introduction

Several categories of efficiency improvement potentials can be distinguished. The *theoretical potential* of energy efficiency improvement for a certain process is determined by thermodynamic laws. The technical minimum is determined by the technological state-of-the-art and is therefore dependent on the time horizon studied. The *technical potential* is defined as the achievable savings resulting from the most effective combination of the efficiency improvement options available in the period under investigation. Applying economic constraints, we can also identify an *economic potential* for energy efficiency improvement, which is defined as the potential savings that can be achieved at a net positive economic effect, i.e. the benefits of the measure are greater than the costs. Investments are assumed to depreciate over the technical life time, at a specific discount rate. The *market potential* is defined as the potential savings that can be expected to be realized in practice, and is determined by investment decision criteria applied by investors under prevailing market conditions.

If economic activities took place under perfect market conditions, all additional needs for energy services would be provided by the lowest cost measures, whether they are energy supply increases or energy demand reductions. There is considerable evidence that substantial energy efficiency investments that are lower in cost than marginal energy supply are not made in real markets. For example, a study estimated that between 6 and 25% of current US energy supply could be replaced by energy efficiency at a cost lower than or equal to energy supply costs [NAS,1991]. Another study found that cost-effective energy efficiency measures in all sectors could reduce energy demand in the year 2015 by about 25% in a "moderate" case and by about 50% in a "tough" case as compared with a baseline in which energy efficiency improvements take place only through market forces [OTA,1991]. The U.S. government's National Energy Plan [DOE,1995a] produced comparable estimates of U.S. energy savings over time. These three studies illustrate that there is increasing consensus that significant amounts of untapped cost-effective energy efficiency exist in advanced economies. Studies of energy efficiency in Europe also indicate large economic potentials, e.g. De Beer et al. (1996), Jochem (1994).

There is compelling evidence that economic potentials for energy efficiency improvements in developing countries are at least as large as in industrialized countries. Levine et al. (1991) estimated energy efficiency opportunities in the developing world of 20-25% of current energy use, with payback periods of three years or less. Another study identified even higher cost-effective electricity savings potential, nearly 50% for a wide range of electricity-using services in developing countries [OTA,1992a]. Achieving such high levels of energy efficiency in developing countries could lead to realization of not only energy but also economic, environmental, and social goals. The energy sector is a serious financial drain in many developing countries, often accounting for as much as 20% of the government's total development budget and often responsible for greater than 40% of total foreign debt in many countries [AID,1988]. If a more balanced energy investment strategy were instituted, resulting in increased investment in energy efficiency and reduced investment in energy supply, developing countries could save significant amounts of capital without sacrificing energy services. Levine et. al. (1991) analyzed a case in which half of electricity services come from new supply and half come from energy efficiency investments in developing countries and Eastern Europe. They estimate a gross reduction in investment in electricity supply over the period 1985 to 2025 to be $2.3 trillion (1990 US$) compared with a scenario meeting the same energy service needs with much lower investment in energy efficiency. Adding the cost of the efficiency investments, the net savings is $1.7 trillion over 40 years or $42 billion per year. These are enormous capital savings for developing countries, which can be put to use in building infrastructure, providing for the health and education of the country, developing and supporting essential development activities.

If there are so many highly cost-effective energy efficiency opportunities, and if investments in energy efficiency have so many desirable effects, why are they not made without the imposition of policies? The existence of such unrealized opportunities implies that there are significant barriers. We first discuss barriers to the investment in and implementation of energy efficiency measures that apply to all economies followed by a discussion of additional barriers that are of particular importance to developing nations.

4.2 Implementation Barriers

There are several barriers to the implementation of energy efficiency improvement measures. We categorize the observed barriers into a few main types, as described below. Empirical quantitative research on the size of the barriers, while limited, underlines the large diversity between individual investors (firms, consumers). More than one of the described measures apply more or less to an investor. The target group has large implications for policy formation aimed at increasing the implementation of energy-efficient measures and equipment.

Willingness to Invest. The decision-making process to invest in energy efficiency improvement, like any investments, is shaped by the behaviour of individuals or of various actors within a firm. Decision- making processes in firms are a function of its rules of procedure [DeCanio,1993], business climate, corporate culture, managers' personalities [OTA,1993] and perception of the firm's energy efficiency [Velthuijsen,1995]. The behaviour has been categorized in a study by EPRI in the US, which determined nine "types" of managers [EPRI,1990], depending on industrial development type and management characteristics. In markets with strong growth and competition, efficiency with respect to energy and other inputs is necessary to survive. In contrast, stagnating markets are poor theatres for innovation and investment, and instead rely on already depreciated equipment to maintain low production costs. A survey of 300 firms in The Netherlands showed that a favourable market expectation was perceived as an important condition for investing in energy efficiency improvement [Velthuijsen,1995]. Also, in markets where increased energy costs can still be recovered in the product price, firms do not have the incentive to invest in energy efficiency improvement. In the same survey in The Netherlands, it also appeared that firms often perceived themselves as energy efficient, even though profitable potentials for energy efficiency improvement were still found [Velthuijsen,1995]. Energy awareness as a means to reduce production costs seems not to be a high priority in many firms, despite a number of excellent examples in industry worldwide (e.g. Dow Chemical in Louisiana, USA, where each year more profitable energy conservation projects are identified in an annual contest with rate of returns far over 100% [Nelson,1994]).

Information & Transaction Costs. Cost-effective energy efficiency measures are often not undertaken as a result of lack of information or knowledge on the part of the consumer, lack of confidence in the information, or high transaction costs for obtaining reliable information [Reddy,1991; OTA,1993; Velthuijsen,1995; Levine et al.,1991; Sioshansi,1991; Levine et. al.,1995]. Information collection and processing consumes time and resources, which is especially difficult for small firms [Velthuijsen,1995] and individual households. An example is provided by Levine and Sonnenblick (1994). In reviewing evaluations of electric utility demand-side management programs, they note that lighting retrofits that result in large energy savings and short paybacks were rejected by the vast majority of building owners and managers until the utility provided a program with large incentive payments for the installation of the systems. In an evaluation of one of the utility programs, more than 65% of the participants (all of whom had rejected the lighting retrofit without the utility program) stated that in the future they would invest in more efficient lighting systems without an incentive. Thus, the utility program transformed the lighting market, with the result that these lighting systems are now accepted without the programs. The authors posit that the utility program was successful as a large-scale demonstration program. Information in the broadest sense of the term was required to achieve market acceptance. The sceptical building managers needed to be convinced that the system would save energy, be cost-effective, could be installed without major disruptions, and would perform as well as the traditional lighting system.

Many individuals are quite ignorant of the possibilities for buying efficient equipment [Reddy,1991], because energy is just one of many criteria in acquiring equipment. The information needs of the various actors are defined by the characteristics of the investor (firm, household), which should lead to a diversified set of information sources. Public authorities and utilities play an important role in providing this information. However, in many developing countries public capacity for information dissemination is lacking, stressing the need for training in these countries. Training is essential, especially in energy conservation planning and policy making [Levine et al.,1991], because of the focus on energy supply in many developing countries [Reddy,1991].

Profitability Barriers. There is compelling evidence that residential consumers substantially under invest in energy efficiency or, stated differently, exhibit high returns to make such investments [Sioshansi,1991]. Meier and Whittier (1983) analysed data from a large number of consumer choices between two refrigerators differing only in the price and energy consumption. They concluded that the consumers typically required a return on investment of 40% or more in order to purchase the more efficient refrigerator. Ruderman et al. (1987) showed that energy efficiency investments in residential equipment exhibited returns of about 20% (for room and central air conditioners), 50 to more than 100% for refrigerators, furnaces, and electric water heaters, and even higher values for freezers and gas water heaters. These numbers, based on data from 1972 to 1980, before mandatory efficiency standards were in effect in the US, reflect both decision making by appliance purchasers and all other factors in the marketplace. For example, if more efficient gas water heaters and freezers are commonly not available in stores (as was the case in the 1970s in the US), then most consumers could not purchase them, at least not without a great deal of effort. The lowest required returns, for air conditioners, reflected the widespread availability of a range of efficiencies.

A large number of standard accounting procedures are available for firms to determine the economic feasibility and profitability of an investment. Surveys showed that many investors use instruments such as simple payback period, rate of return or net present value (also in economies in transition) to evaluate energy efficiency projects. When energy prices do not reflect the real costs of energy, then consumers will necessarily under invest in energy efficiency. Energy prices, and hence the profitability of an investment, are also subject to large fluctuations. The uncertainty about the energy price, especially in the short term, seems to be an important barrier [Velthuijsen,1995]. The uncertainties often lead to higher perceived risks, and therefore to more stringent investment criteria and a higher hurdle rate [Hassett and Metcalf,1993].

An important reason for high hurdle rates is capital availability. Capital rationing is often used within firms as an allocation means for investments, leading to even higher hurdle rates, especially for small projects with rates of return from 35 to 60%, much higher than the cost of capital (~15%) [Ross,1986]. On the supply side the costs of capital are much lower, leading to imperfections of the capital market. Utilities and investors in power supply typically operate with payback periods of 20 years or longer. These capital market imperfections lead to bias against end-use investments vis-a-vis energy supply. This also seems to apply to international loans. From this perspective, energy efficiency investments in developing countries are put at a disadvantage [Levine et al.,1994].

Management or Organisational Barriers. The literature suggests that the fewest barriers to energy efficiency investment exist in the industrial sector, where managers are thought to be motivated by cost minimization [Golove,1994]. However, DeCanio (1993) has shown that firms typically establish internal hurdle rates for energy efficiency investments that are higher than the cost of capital to the firm. Figure 4.1 shows shares of firms willing to make an investment with a given maximum payback period, based on surveys of firms in Germany [Gruber and Brand, 1993] and the Netherlands [Koot et al.,1984].

Lack of skilled personnel. Especially for households and small and medium sized enterprises (SME) the difficulties installing new energy-efficient equipment compared to the simplicity of buying energy may be prohibitive [Reddy,1991]. In many firms (especially with the current development toward *lean* firms) there is often a shortage of trained technical personnel [OTA,1993], because most personnel are busy maintaining production. A survey in The Netherlands suggested that the availability of personnel is seen as an barrier to invest in energy-efficient equipment by about one third of the surveyed firms [Velthuijsen,1995]. In the EITs the disintegration of the industrial conglomerates may lead to loss of expertise and hence similar implementation problems. Outsiders (consultants, utilities) are not always welcome, especially if proprietary processes are involved [OTA,1993]. In developing countries there is hardly any knowledge infrastructure available that is easily accessible for SMEs. Such knowledge is important because SMEs are often a large part of the economy in developing countries, and are often inefficient. In addition, the possible disruption of the production process is perceived as a barrier, leading to high *transition costs*. Transition costs may include the costs of not fully depreciated production equipment, although the investment in itself may be economically attractive. The size of the transition problems may be reduced by maintaining a good infrastructure for efficiency improvement. This seems especially true for small consumers (households, SMEs).

Other Market Barriers. In addition to the problems identified above, other important barriers include (1) the "invisibility" of energy efficiency measures and the difficulty of demonstrating and quantifying their impacts; (2) lack of inclusion of external costs of energy production and use in the price of energy, and (3) slow diffusion of innovative technology into markets. A full discussion of these topics is beyond our scope (see [Levine et al.,1994; Fisher and Rothkopf,1989; Sanstad and Howarth,1994]). Many companies are risk averse with regard to a possible effect on product quality, process reliability, maintenance needs or uncertainty about the performance of a new technology [OTA,1993]. Firms are therefore less likely to invest in new not yet commercially proven technology. Aversion of perceived risks seems to be a barrier especially in SMEs [Yakowitz and Hanmer,1993].

There are other barriers to energy efficiency in residential markets. For dwellings that are rented, there are few incentives for the renter to improve the property that he/she does not own; similarly, the landlord is uncertain of recovering his/her investment, either in higher rents (as it is difficult to prove that improved thermal integrity will save the renter money in utility bills) or in the utility bills, as the bills depend on the behaviour of the renter [Fisher and Rothkopf,1989; Sanstad and Howarth,1994]. The same sort of problem can exist in commercial buildings between builders and owners. Builders are often required to minimize first costs in order to win bids, and many building owners do not have sufficient expertise to recognize the benefit of higher first costs to reduce building operating costs [Golove,1994]. Likewise, utilities have the incentive to promote greater energy use, not to promote greater efficiency by their customers, unless markets are transformed [Baxter,1995].

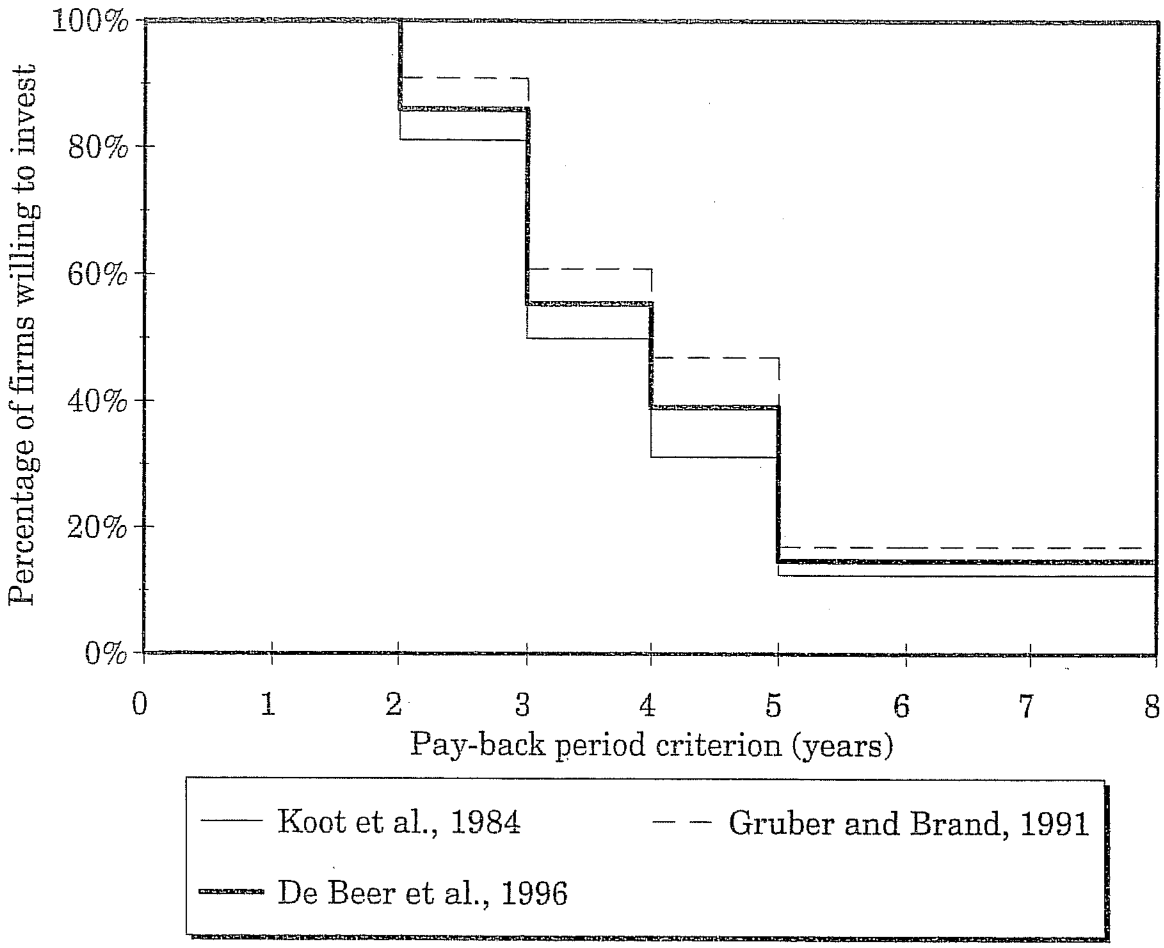

Figure 4.1. Shares of firms willing to make an investment with a given maximum payback period, determined on the basis of surveys of several firms in the German [Gruber and Brand,1993] and Dutch industry [Koot et al.,1984]. The bold line depicts an average curve [De Beer et al.,1996].

Additional Barriers to Energy Efficiency in Developing Countries. Developing countries suffer from all of these factors that inhibit market acceptance of energy-efficient technologies plus a multitude of other market problems. Energy costs in industrialized countries often do not reflect the total costs, but the problem is especially serious in developing countries, where energy is very considerably underpriced, with the government providing the energy supply industries (especially electric power producers) large subsidies for them to stay in business. Environmental externalities are also likely to add significantly to the social cost of energy production in developing countries because environmental control technologies are generally less used. Because energy pricing issues are such an important aspect of energy policy reform in developing countries, we address this issue, as well as the difficulties in raising energy prices and ways that these difficulties may be overcome, in section 4.3.

Consumers often have no knowledge of energy efficiency and, if they did have knowledge, often cannot afford even small increases in equipment costs. Reddy (1991) makes the important point that the problem of this knowledge gap concerns not only consumers of end-use equipment but all aspects of the market. Many producers of end-use equipment have little knowledge of ways to make their products energy efficient, and even less access to the technology for producing the improved products. End-use providers are often unacquainted with efficient technology. Producers and distributors of energy carriers pay no attention to measures to reduce energy demand because all of their incentives are linked to increasing supply. Financial institutions are hesitant to take risks in promoting new technology to an even greater degree than in industrialized countries. The government itself is little involved in providing the essential information necessary for consumers to make intelligent choices on energy efficiency. Indeed, in many developing countries it is the government that owns and operates the energy supply companies; in these cases, the government often suffers from the same supply biases as the utilities that it runs. These energy supply companies often have significant political power, which often counteracts the efforts of agencies of government that promote energy efficiency (if they exist at all). This presents a particularly vexing problem for energy efficiency in developing countries, as a governmental leadership role is essential to overcome the considerable imperfections in the markets of these countries. Active support of energy efficiency programs by multilateral and bilateral lending and aid organizations could strengthen advocates of energy efficiency in developing countries. However, these international institutions are not yet confident that they know how to use their resources to effectively promote increased energy efficiency. An additional barrier is the often unstable economy characterized by high inflation and unstable exchange rates which discourage long term investments.

Gadgil and Sastry (1994) stress that rigid hierarchical structure of organizations and the paucity of organizations occupying the few niches in a given area, lead to strong and closed networks of decision makers who are often strongly wedded to the benefits they receive from the status quo. They describe how the hierarchy in India led to the discontinuation of an innovative program for a utility to lease compact fluorescent lamps to its customers. Nadel (1991a), in studying difficulties in adopting energy efficiency in India, describes at least ten major barriers: lack of information about products; limited ability to pay even small increased first costs; very low electricity prices; limited foreign currency (which makes difficult the purchase of modern equipment from outside the country); poor power quality (which often interferes with the operation of the electronics needed for energy-efficient end-use devices); shortage of skilled staff to select, purchase, and install efficient equipment; a large used equipment market which keeps inefficient equipment operating long after its useful life; high taxes that increase the first cost differential between efficient and inefficient products; and the very high risk aversion of the lending community; and many small and/or outdated industrial activities that do not have resources to produce efficient equipment.

4.3 Policy Instruments

A critical issue for this report is what policies and programs can be carried out to overcome the barriers to cost-effective energy efficiency. We group our discussion of policies as follows: (1) energy price reform and other economic instruments, (2) regulations and guidelines, (3) voluntary agreements and programs, (4) information programs, and (5) research, development, and demonstration. We include "other economic instruments" under (1) to encompass a wide variety of policy approaches that rely on market forces and are not included in the other categories.

In addition to considering policies that can be implemented by individual nations, we also address the important topic of how industrialized countries and international organizations can most effectively work with developing countries to promote effective end-use energy efficiency programs. We believe that this is a particularly important topic, and one that has received inadequate attention among decisionmakers concerned with improving the well-being of developing nations.

4.3.1 Energy Price Reform and Other Economic Instruments

Energy Prices. Markets are a powerful and fundamental force in wide-scale implementation of energy efficiency. Subsidies that depress prices of energy provide a significant disincentive for energy efficiency. The removal of this barrier (low energy prices) is an important step toward creating an investment climate in which energy efficiency can prosper [Anderson,1995; Bates,1993; Munasinghe,1992].

Worldwide, consumer energy prices typically do not reflect the full costs of energy production, transmission, and distribution because these prices are often subsidized. Furthermore, the energy prices do not include environmental costs. In 1991, world fossil fuel subsidies reduced consumer energy prices by 20 to 25%. Subsidies are greatest in the developing countries and in EE/FSU, with the bulk of global fossil fuel subsidies in the latter region [Kozloff and Shobowale,1994]. Between 1979 and 1991, electricity prices in developing countries were on average 40% lower than electricity prices in OECD countries. The disparity grew over the period from an average difference of 2.3 cents/kWh (1986 US$) between 1979 and 1984 to an average difference of 3.4 cents/kWh between 1985 and 1991 (see Figure 4.2). A survey of electricity prices of over 60 developing countries found that electricity subsidies grew during the 1980s [World Bank,1990]. In 1991, the average electricity price in developing countries was 4 cents/kWh while the marginal costs were about 10 cents/kWh [Heidarian and Wu,1994]. Comparison of retail electricity prices to the marginal costs of supply found ratios of 50 to 60% in China, 66% in Brazil, 29% in Poland, and 63% in Mexico in the late 1980s [Bates,1993].

Energy prices in some areas are beginning to more closely reflect costs in response to commercialization of the electricity industry and investment by independent power producers [Anderson,1995]. For example, Thailand has essentially eliminated across-the-board subsidies, electricity prices in Korea have reached the level of costs, and energy prices in Poland are being adjusted to reflect full economic costs [World Bank, 1993; Larsen and Shah,1992; Polish Ministry of Industry and Trade,1992]. In Chile, energy prices rose following power sector privatization and reforms that eliminated government intervention in setting prices. In Colombia, Peru, Jamaica, Costa Rica, and Bolivia, privatization of part or all of the energy supply industry is currently taking place, and is expected to lead to deregulation of electricity prices in these countries [Bacon,1995]. After many years of trying, the Chinese government initiated significant energy price reforms starting in 1993. By 1994, 90% of all coal was no longer subject to price regulations, and the price of this coal reflected most of the supply costs. In 1993, electricity price reforms in China led to prices for new power projects based on the cost of generation plus a return on capital. This change, plus higher prices for power from existing power plants, means that electricity prices may in time approach deregulated, marginal costs [Wang et al.,1996].

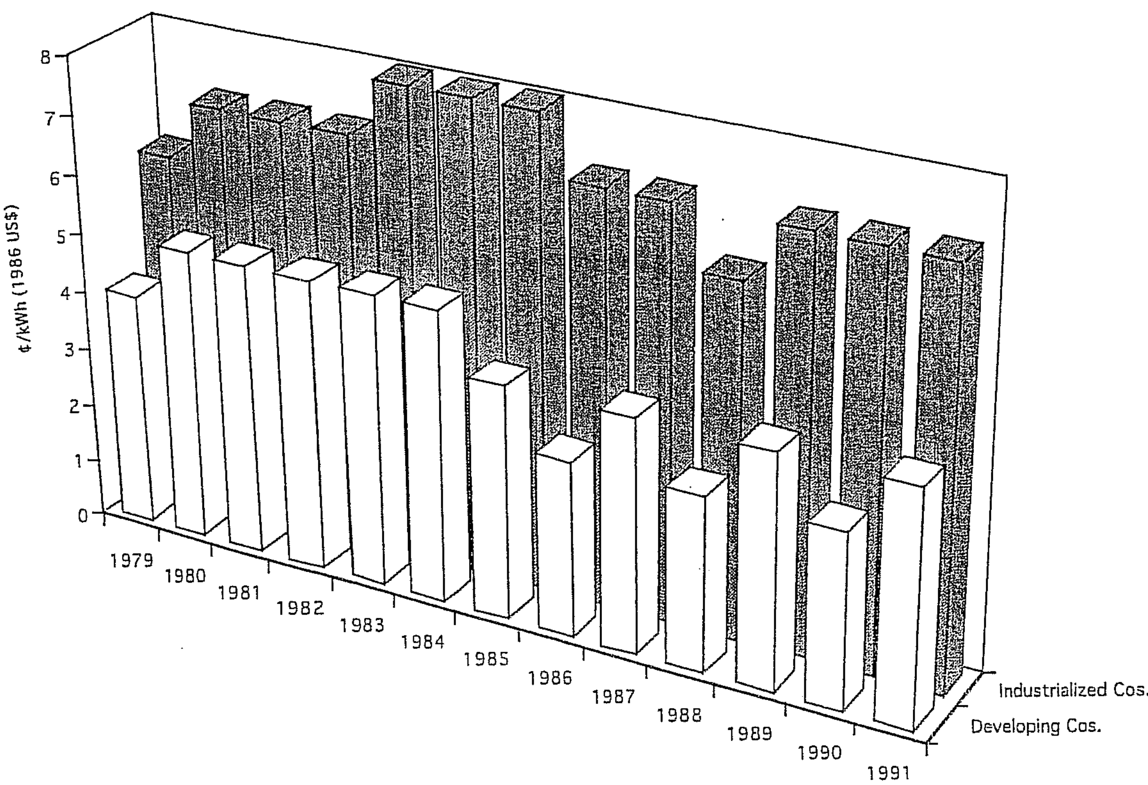

Figure 4.2 Average electricity prices (in UScts(1986)/kWh) in industrialized and developing countries for the period 1979-1991. The figures have been corrected on the basis of exchange rates to 1986 US$.

The international lending organizations, led by the World Bank, have been strong proponents of energy price deregulation in developing countries. The largest hurdle to such price increases involves the impact on low-income consumers. This is a serious problem in many developing countries, as low-income urban families often spend a substantial portion of their income on energy. Recent surveys in urban areas of developing countries show the poorest 20 percent of the population spending 20 percent of their income on energy [Barnes et al.,1994]. It should be noted that very often in DCs the poorest have no access to commercial energy use at all. The impacts of higher energy prices on the urban poor can be mitigated in several ways. A low tariff for the lowest consumption block can be instituted, the so-called "lifeline rate" in the USA. Subsidies for energy efficiency improvements can be targeted at low-income urban dwellers. Such subsidies could moderate an increase in energy services. Because the lowest income population consumes a relatively small proportion of total energy in developing countries, revenue obtained from energy price increases would be expected to far exceed any subsidies to the low-income consumers. The main points are that (1) removal of energy price subsidies is a very important step to achieving end-use energy efficiency in most developing country economies, (2) that removal of subsidies is very unlikely without protecting low-income consumers, and therefore (3) increased attention to innovative ways to protect these consumers is needed.

Other Economic Instruments. Numerous policy instruments have been used to provide economic incentives to promote energy efficiency in industry, buildings, and transportation. These instruments include subsidies and tax credits, utility integrated resource planning, and other market mechanisms [DOE,1989].

Direct subsidies and tax credits or other favourable tax treatments have been a traditional approach for promoting activities that are thought to be socially desirable. Incentive programs need to be carefully justified to assure that social benefits exceed costs. Direct subsidies might also suffer from the 'free rider' problem where subsidies are used for investments that would be made anyway. Estimates of the share of 'free riders' in Europe range from 50 to 80% [Farla and Blok,1995], although evaluation is often difficult. However, other subsidy programmes, e.g. the federal grants in the USA for weatherization of houses of low-income families, show low free riders. An interesting type of subsidy has been the provision of low interest loan funds for energy efficiency projects, with the government absorbing the difference in interest payments. Examples of such instruments applied to energy include the favourable tax treatment that was given wind generators in the US to support the creation of a new industry, tax credits that have been given by a number of governments for active solar energy systems, and the favourable tax treatment given to non-fossil producers in many industrialized countries. In some European countries experiments with so-called 'green' funds, that provide low-interest loans, from private funds, seem favourable.

An example of a financial incentive program that has had a very large impact on energy efficiency is the energy conservation loan program that China instituted in 1980. This loan program is the largest energy efficiency investment program ever undertaken by any developing country, and currently commits 7% to 8% of total energy investment to efficiency, primarily in heavy industry [Sinton et al.,1995]. The program not only funded projects that on average had a cost of conserved energy well below the cost of new supply, it also stimulated widespread adoption of efficient technologies beyond the relatively small pool of project fund recipients [Levine and Liu,1990; Liu et al.,1994]. The program contributed to the remarkable decline in the energy intensity of China's economy. Since 1980 energy consumption has grown at an average rate of 4.8% per year (compared to 7.5% in the 1970s) while GDP has grown twice as fast (9.5% per year), mainly due to falling industrial sector energy intensity. Of the apparent intensity drop in industry in the 1980s, about 10% can be attributed directly to the efficiency investment program [Sinton and Levine,1994], and a larger amount from unsubsidized efficiency investments, efficiency improvements incidental to other investments, and housekeeping measures.

Utility **Integrated resource planning (IRP)**, which has been applied primarily in industrialized countries, is used to assess all options for meeting energy service needs, including utility-sponsored end-use efficiency programs. The novel feature of IRP is that it requires utilities to look beyond the utility meter and into the ways that electricity is used, in order to find the least-cost way of providing energy service. IRP programs in the US have shown a wide variety of end-use efficiency measures that are less costly than energy supply additions. Two major problems occur: (1) inducing the utility to carry out end-use efficiency programs and (2) designing these programs so that they are in fact cost-effective. In the US, utilities have traditionally been subject to rate of return regulation, i.e. the utility obtains profit from its "rate base," consisting of its investment in generation, transmission, and distribution. This results in a strong disincentive for end-use efficiency programs. This is a dilemma: while the end-use efficiency is desirable from an individual consumer and a social perspective, the utility has strong incentives to increase supply and disincentives to reduce demand under rate of return regulation. In the early 1980s, a new approach provided incentives to utilities for promoting end-use efficiency programs. These incentives consisted of (1) recovery of all costs of carrying out the programs, (2) increased profits for demonstrated successful end-use efficiency programs, (3) recovery of foregone profits resulting from reduced sales. This represents a transfer of financial resources from the ratepayer to the utility -increasing the utility profitability- and was extremely successful in promoting utility end-use efficiency programs. Baxter (1995) shows that certain types of regulatory reforms that remove the financial disincentives could lead to increased utilitty energy efficiency investments in the US. US utility expenditures on demand-side management (DSM) programs tripled in 5 years to $3 billion in 1994 [Hadley and Hirst,1995]. The 25 utilities with the largest estimated energy savings resulting from these programs, representing 25% of the total electricity sales, spent an average of 2.1% of revenues on these programs [Hadley and Hirst,1995]. Perhaps most remarkably, utility expenditures on DSM in the early 1990s were between 7 and 10% of expenditures on all supply and transmission and distribution.

There have been many evaluations of individual utility DSM programmes, and most have been shown to be more cost-effective than energy supply. It is, nonetheless, difficult to accurately measure the performance of these programmes. Electricity used is a measurable quantity. Electricity saved is much more elusive. We have seen earlier that the relative invisibility of energy savings acts as a disincentive to consumer investment. It is not easy to overcome consumer scepticism, even of energy efficiency measures that perform extremely well, when evidence for success is uncertain in the absence of extensive statistical studies. One study, which placed evaluations of $190 million of commercial lighting programs in 20 utilities on a common basis, including all costs and energy savings of the programs, showed an average cost of energy savings for these programs to be 3.9 cents per kWh. This is considerably less than the marginal cost of new power at the time the programs were implemented [Eto et al.,1994]. With a widespread belief that many aspects of the utility industry in the US will be deregulated over the coming years, and the efforts that many utilities are taking to improve their competitive position, the regulatory reforms to make DSM attractive to utilities are working less well. As a result, utility DSM programs have begun to decline.

There has been interest in IRP and the establishment of DSM programs in many developing countries. Thailand has launched a multi-sectoral DSM program to invest US$ 180 million over five years that is aimed at saving 225 MW of peak demand and 1,000 GWh annually. This is estimated to be half the cost of new supply. The program includes design assistance for new commercial buildings, as well as lighting retrofits in existing buildings [Busch,1994]. China has also shown considerable interest in IRP, with several utilities developing plans. Utilities in Mexico and Brazil have been active in DSM programs. Brazil's national electricity conservation programme (PROCEL) is estimated to have saved the equivalent of a 250 MW power plant. The cost benefit ratio was estimated to be more than ten to one, with savings of 500 MUS$ and programme costs of 35 MUS$ [Tavares,1995].

Other market mechanisms intended to achieve results similar to regulatory programs but without a "command and control" approach have come to be known as market mechanisms. They generally have two features: (1) they depend on market decisions for their effectiveness and (2) they are generally revenue neutral (i.e., do not represent any increase in government expenditures). It is the second attribute that has made these programs of particular interest during times of tight governmental budgets. These types of programs have been tried as alternatives to regulation in environmental control. For example, use of pollution trading mechanisms is an innovative way of achieving environmental standards, potentially at much lower cost than command and control approaches. So-called 'feebate' programs involve a rebate to reward a desired action or decision combined with a fee to penalize an activity that is not desired. Feebate programs have been proposed as alternatives to more stringent energy efficiency standards for new automobiles in the US [DOE,1995c].

An innovative policy mechanism to transform the market towards the production and consumption of more efficient products is "**market aggregation**", or the organized use of buyer demand to stimulate new supplies of a product or service [Harris,1995]. If a significant share of buyers of a given type of product demand a more efficient product, then this can "pull" the market to a more efficient product mix. Government agencies can play a key role in aggregating the buyers to reduce risk for the producer, and providing incentives for the production of more efficient products. Market pull activities are now gaining greater interest in industrialized countries, and eventually could be a model for developing countries. NUTEK, the Swedish National Board for Industrial and Technical Development, has successfully undertaken several technology procurement projects for more efficient refrigerator-freezers, laundry equipment, high-performance windows, computer monitors, office lighting, electronic ballasts and other products [Harris,1995; Lewald and Bowie,1993]. In the US, recent activities include a Federal "Procurement Challenge" which directs all Federal agencies to purchase energy-efficient products that are in the top 25% of the market. Other voluntary programs are the so-called "Golden Carrot" programs, applied in Sweden and the USA. The first in the US involved utility subsidies to design and produce a refrigerator more efficient than the level set by the appliance standards. A design competition was held, with one winning manufacturer, Whirlpool, that built and sold these refrigerators. The design has become the basis for the next generation of refrigerators. Golden carrot programs have been launched for clothes washers, heat pumps, central air conditioner, electric water heaters, and gas heaters [EPA,1994].

Energy service companies (ESCOs) provide energy savings services to consumers either directly or through utility demand-side management programs. ESCOs typically provide engineering and managerial expertise to help customers assess and implement energy efficiency improvements. These companies assume technical, financial, and operational risks as well as arrange project financing. ESCOs then either receive a fee based on achieved energy savings [Levine et al.,1992] or sign a contract for the provision of energy savings at specified prices [Goldman and Kito,1994]. About 30 US utilities used ESCOs as a component of their DSM programs to reduce demand in residential, commercial, and industrial facilities between 1987 and 1994 [Goldman and Kito,1994].

4.3.2 Regulations and Guidelines

Regulatory programs have proven effective in promoting energy efficiency gains. Examples include appliance energy efficiency regulations, automobile fuel economy standards, and commercial and residential building standards programs. In such programs the government passes a requirement that all products (or an average of all products sold) meet some minimum energy efficiency level. Energy efficiency standards are applied in many countries for various energy uses [IEA,1992]. Standards can be performance based, i.e. they do not mandate how the manufacturer is to meet them (i.e., what technologies or design options to use) and are used for appliances or cars (e.g. the *CAFE* standards in the US).

Appliance energy efficiency standards have been aggressively pursued in the US. Since the passage of the National Appliance Energy Conservation Act (NAECA) by the U.S. Congress in 1987, the federal government has mandated standards for such products as refrigerators, water heaters, furnaces and boilers, central air conditioners and heat pumps, room air conditioners, clothes washers, dryers, and dishwashers, ovens, and lighting ballasts. NAECA requires a periodic update on all standards, with the timing of new standards differing among different products [Geller,1995]. From the viewpoint of economic and energy savings, these standards have been a major success. The standards already in effect are expected to reduce energy consumption in the US by 1.1 EJ/year by the year 2000 and 2.75 EJ/year by 2015, avoiding the equivalent of 31 500 MW power plants by the year 2000. The standards are based on promoting only cost-effective energy efficiency measures. Standards that are presently under evaluation have the potential to substantially increase the savings above these estimates, because of possible increased stringency and because new legislation permits the inclusion of additional products (especially distribution transformers, small motors, and lighting systems).

The auto fuel economy standards were promulgated in the US at a time (1975) when US autos consumed about 80% more fuel per vehicle mile than a European or Japanese auto. By 1992, the average US automobile consumption had declined from 18 litres/100km to 12 litres/100km, while the European and Japanese fuel intensities changed very little [Schipper,1995a]. Much of this reduction in fuel intensity was a result of the standards; however, during the period in which the greatest increases in fuel economy occurred, real gasoline prices tripled. Estimates of the impact of the standards by themselves vary between 15 and 50% out of the total savings gained for new automobiles [OTA,1994]. There is currently considerable debate about the magnitude of savings possible by promulgating more stringent standards to increase fuel economy. The timing, cost, and magnitude of fuel economy improvements is a crucial question to be answered to determine the desirability of new, more stringent fuel economy standards. However, in the US, it appears unlikely that more stringent standards for automobiles will be adopted.

Building energy standards may be performance or component standards. Almost all residential standards specify the measures to be included in the building to comply. Some of them also have an alternative or performance pathway, in which the builder may choose different combinations of measures to meet a specified performance level. Second, the actual energy savings from building energy standards are more difficult to estimate than for appliances and automobiles, as, firstly, buildings are not mass-produced.[16] Where performance standards are used (primarily for large commercial buildings), the standard is a design standard, meaning that the design, rather than the building itself, needs to meet the code. Faulty construction practice is not dealt with, and typically is responsible for a significant share of poor energy performance of buildings. Thirdly, the operation of a building, which is not affected by building energy codes, plays a major role the actual performance of buildings. Building commissioning, where systems are tested and maintenance personnel are trained to ensure correct performance of systems, could help deal with this problem for new buildings. In spite of these limitations on energy standards for buildings, they are important policy tools. Because buildings are extremely long-lived, consume large quantities of energy, and can be made more energy efficient at much lower cost when new than after they have been built and occupied, even energy standards that in their implementation are far from perfect can still yield significant economic and energy benefits. Building energy standards are in use or proposed in a large number of countries. A survey of energy standards that received replies from 57 countries, more than half of which do not belong to the OECD, revealed that 27 had mandatory standards (of which four were residential only and two were commercial only), 11 had voluntary or mixed standards, 6 had proposed standards, and only 13 (all developing countries)

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16 To assure performance every individual building has to be tested to assure performance. In practice, buildings are not tested and the degree to which post-standards buildings meet the standards has been established through a small number of experiments.

had no standard [Janda and Busch,1993]. The issue of the degree of success of these standards in buildings as built and operated is still a major issue.

4.3.3 Voluntary agreements.

A voluntary agreement generally is a contract between the government (or another regulating agency) and a private company, association of companies or other institution. The content of the agreement may vary. The private partners may promise to attain certain energy efficiency improvement, emission reduction target, or at least try to do so. The government partner may promise to financially support this endeavour, or promise to refrain from other regulating activities.

Some examples of voluntary agreements directed at energy efficiency improvement are discussed below (for an overview, see [IEA,1996]). Agreements have been reached between the Netherlands government and (associations of) *industrial companies* to improve the energy efficiency in the year 2000 by 20% compared to the 1990 situation [Ministry of Economic Affairs,1995]. Also in Denmark agreements can be closed between the government and industrial companies; the latter have to take all energy conservation measures that have a pay-back period less than 4 to 6 years. Companies that enter into such an agreement are exempted from paying the Danish carbon tax [Danish Government,1995]. Also in other countries, like Finland, Germany and Switzerland similar agreements have been reached or are under way. The U.S. Environmental Protection Agency (EPA) has created voluntary programs to reduce greenhouse gas emissions in *buildings* [EPA,1994]. These programs are known as EPA's "green programs." The Green Lights program, launched in 1990, involves an agreement between EPA and corporations in which the corporation commits to all cost-effective lighting retrofits and EPA commits to providing technical support. By 1994, Green Lights had 1682 participants, including 37% of the Fortune 500 firms, representing 130 million m^2 of floor space. EPA estimates that the program saved 1 TWh of electricity in 1994 [EPA,1995]. Other green programs include Energy Star Computers, which achieved agreement of the major manufacturers to provide energy-saving features on their computers, and Energy Star Buildings. An agreement has been attained between the US government and the big three *car manufacturers* in the USA, with the goals of producing a prototype car with a specific fuel consumption three times lower than the 1994 cars in the year 2005 [PNGV,1994]. German car manufacturers have given a voluntary statement to reduce the specific fuel consumption of cars they make and sell in the year 2005 by 25% compared to the year 1990. A special type of agreement is an agreement between the Netherlands' government and the Netherlands' *utilities* (energy distribution companies) in which the latter promised to put in place DSM programmes good for 17 Mtonne of CO_2 emission reduction before the year 2000 [EnergieNed,1994].

There has been much experience with voluntary agreements in the Netherlands, especially in the field of waste management policy and toxic emissions policy. The experiences varied strongly - from successful actions to complete failures [Van Rossum,1988; Klok,1989]. In some cases the result of a voluntary agreement may come close to those of regulation. Note that also in the case of regulation there often are aspects of 'agreement', such as the negotiation between the regulating body and the regulated party [Marcus,1980]. Voluntary agreements can have some apparent advantages above regulation, in that they may be easier and faster to implement, and may lead to more cost-effective solutions. At this stage it is not yet clear what role voluntary agreements could play in energy and material efficiency policy. As a preliminary guideline for application of voluntary agreements an advice of the advisory council on environment in the Netherlands may still be valid. This council stated that voluntary agreements may play a useful role in anticipation on or in addition to physical regulation if some conditions are met, e.g. the government is leading in setting the policy and democratic decision making is warranted. Furthermore, voluntary agreements should ultimately be converted to regulation [CRMH,1989].

4.3.4 Information Programs

Information programs are designed to assist energy consumers in understanding and employing technologies and practices to use energy more efficiently. These programs aim to increase consumers' awareness, acceptance, and use of particular technologies or utility energy conservation programs. Examples of information programs include educational brochures, hotlines, videos, home energy rating systems, design-assistance programs, audits, energy use feedback programs, and labelling programs. As noted before, the information needs are strongly determined by the situation of the actor. Therefore, successful programs should be tailored to meet these needs. A German survey showed that trade literature was the most important source of information followed by personal information from equipment manufacturers [Gruber and Brand,1991]. A Dutch survey showed that exchange between colleagues was also an important information source [Velthuijsen,1995].

Information programs are often components of larger energy efficiency activities, so evaluations of their effectiveness is limited. Information programs by themselves have been shown to result in energy savings of 0 to 2% [Collins et al.,1985]. A US utility that launched a 2-year advertising promotional campaign for energy efficiency found that participation rates in their programs often doubled, but that savings were not necessarily persistent for long periods [Auch & McDonald,1994]. Developing countries such as China, Brazil, Mexico, India, and Thailand have developed large-scale information programs to promote lighting and other residential technologies, although few detailed assessments exist on the effectiveness of these efforts. In general, information campaigns are most effective when the provider is a trusted organization and when the information is provided face-to-face [Nadel,1991].

Energy audit programs are a more targeted type of information transaction than simple advertising. Residential energy audits performed in the US in the 1980s have been shown to have average net savings of 3 to 5% with benefit/cost ratios between 0.9 and 2.1 [Hirst,1984; OTA,1992a]. Commercial and industrial customers that received audits reduced their electricity use by an average of 2 to 8%, with the higher savings rates achieved when utilities followed up their initial recommendations with strong marketing, repeated follow-up visits, and some financial incentives to implement the recommended measures [Nadel,1990; Nadel,1991]. Energy audit programs exist in numerous developing countries, and an evaluation of programs in 11 different countries found that on average 56% of the recommended measures were implemented by audit recipients [Nadel et al.,1991a].

Education and training both for customers and for industrial energy managers offers perhaps the greatest potential for achieving long term energy efficiency savings. The importance of training for developing countries is highlighted below. For industrialized countries, training has often proven to be a highly cost-effective option for achieving savings. One US utility measured the effect of weatherization energy efficiency education for low-income customers and found annual savings 8% higher than for customers who did not receive the information and training [Harrigan and Gregory,1994]. The U.S. Climate Change Action Plan relies on information programs to capture about 5% of overall CO_2 emission reductions [DOE,1994].

These examples and others point to the fact that better information, training and audits have a role to play in energy-efficiency policies. However, information alone has not been very effective in getting consumers to actually commit to purchase energy efficient products. Analyses of consumer information programs in the US found that these programs alone generally result in much less energy savings than expected. However, information programs combined with various other approaches can be very effective. In particular, utilities have combined information programs with incentives for energy efficiency [Energiened,1994], with favourable results. People are much more likely to pay close attention to information if they are likely to use it; incentive programs which get the attention of consumers, when combined with the provision of high-quality information, have proved to be successful in many utilities [Geller and Nadel,1994, OTA,1992a]. Information programs (e.g., labels for appliances and other information derived from test procedures) provide the necessary underpinnings for other energy efficiency policies.

4.3.5 Research, Development and Demonstration (RD&D).

RD&D comprises creative work undertaken on a systematic basis to increase the stock of knowledge, including knowledge of people, culture and society, and the use of this knowledge to devise new applications. Different stages of RD&D can be distinguished, basic research, applied research, experimental work and demonstration [OECD,1993]. RD&D can have various goals, depending on the barriers to be tackled to implement a technology. Blok et al. (1995) differentiate between technical development of a technology, improving the technology to reduce costs, and exploration and alleviation of barriers to the implementation of a technology.

The challenge of climate change is to achieve deep reductions over time, which can only be reached by building (technological) capacity through sustained RD&D efforts. Large potential efficiency improvements do exist on the long term, e.g. the possible contribution of RD&D for energy efficiency improvement in industry is estimated at 15% (in the European Union until the year 2020) additional to a savings potential of 25% feasible with existing technologies [Blok et al.,1995]. The study estimates similar or larger potentials in other sectors. A recent report by the US Department of Energy (1995b) quotes many successes of energy RD&D in various energy fields. There is consensus among economists that R&D has a payback that is higher than many other investments, and the success of R&D has been shown in fields like civilian aerospace, agriculture and electronics [Nelson,1982]. Still the private sector has a propensity to under invest in RD&D, because it cannot appropriate the full benefits of RD&D investments, due to 'free riders' (firms that imitate but don't bear the costs of the RD&D) [Cohen and Noll,1994].

Firms will also under invest in RD&D that reduces costs not reflected in market prices [Williams and Goldemberg,1995], such as air pollution damages and climate change. Currently, widespread cutbacks in energy RD&D, both public as private, threaten the continuity of the RD&D efforts [DOE,1995b]. US energy RD&D funds have decreased by 65%, and by 33% in other OECD countries between 1977 and 1992 [Williams and Goldemberg,1995]. Industrial energy RD&D expenditure in the US decreased from 0.13% to 0.08% of GDP in the same period, cutting back mainly in basic research [Williams and Goldemberg,1995]. This trend is expected to continue, as many utilities and industries are reducing costs to compete in more open markets.

Williams and Goldemberg (1995) defined the following criteria for energy RD&D. *Align energy RD&D priorities* with climate change policy goals. Less than 6% of the energy R&D budget of IEA countries in 1990 was spent on energy conservation and 6% was spent on renewable energy, while spending on nuclear fusion (46%), nuclear fission (11%) and fossil energy (18%) dominated [IEA,1994]. RD&D should be a *sustained activity*, because it takes large resources to build up a knowledge infrastructure, and the key to success is so-called 'tacit knowledge' (unwritten knowledge obtained by experience) [Dosi,1988], which is easily lost. A *diversified portfolio* is needed, as not all RD&D will lead to commercialization. Priority to relatively small-scale technologies like energy efficiency and renewables allows a diversified portfolio with limited budgets. A diversified portfolio makes it also possible to meet the different RD&D demands of industrialized and developing countries. Finally, *long term research* should be protected against the often more costly demonstration and commercialization initiatives. Sustainable energy policies should secure continuity of RD&D funds by appropriate funding mechanisms: public funding of valuable RD&D that it is not executed by industry, and cost-sharing of RD&D [DOE,1995b] where both private and public benefits are produced.

4.4 Cooperation between Industrialized and Developing Countries

Efforts to promote energy efficiency in both industrialized and developing countries have illuminated the need for closer collaboration between these countries, especially in the areas of technological innovation, strengthening of local capacity, increased training and information. Experience has shown that energy efficiency should be more carefully integrated into development policies.

There is great need for **technological innovation** for energy efficiency in the developing countries. The technical operating environment in these countries is often distinctly different from that of industrialized countries. For example, poorer power quality, higher environmental dust loads, and higher temperatures and humidity require different energy efficiency solutions than those successful in industrialized country conditions. Technologies that have matured and been perfected for the scale of production, market, and conditions in the industrialized countries may not be the best choice for the smaller scale of production or different operating environments often encountered in a developing country. Energy-efficiency innovations will need technology development, field tests, and support for technology maturation and market acceleration. Strenghtening of cooperation between DCs could also be an important driver for innovation and building capacity. This could be through joint-ventures, licensing or local subsidiaries. However, there is a lack of technical infrastructure and shortage of technical workers in many developing countries. Industrialized and developing countries need to cooperate both in applying science and engineering skills to development of technologies and in sharing the risk of such innovations. The demonstration projects of advanced technologies pursuit by UNDP are a good example of the latter.

An important arena for cooperation between the industrialized and developing countries involves the **development** and **strengthening** of **local technical** and **policy-making capacity**. Project-oriented agencies eager to show results commonly pay inadequate attention to the development of institutional capacity and technical and managerial skills needed to make and implement energy efficiency policy. Industrialized and developing countries need to cooperate to provide training and experience for energy efficiency policymakers from developing countries, extended exchange visits between governmental and non-governmental organizations (NGOs) from the industrialized and the developing world, offer financial and technical support for the creation and strengthening of centers for energy efficiency technology and policy analysis in the developing countries.

Cooperation between the industrial and developing countries to systematically address the need for training and information is essential. Regional training centers and information systems should be founded and supported in developing countries, similar to those that are in operation in Eastern Europe. Industrialized and developing countries could cooperate in the founding and operation of the centers, as well as in the funding for the training courses, information systems, analyses, and dissemination of information regarding energy efficiency policy and programs.

Energy efficiency should be viewed as an **integral component** of national and international development policies. Energy efficiency is commonly much less expensive to incorporate in the design process in new projects than as an afterthought or a retrofit. In the environmental domain, we have learned that "end of pipe" technologies for pollutant clean-up are often significantly more expensive than project redesign for pollution prevention, leading to widespread use of pre-project environmental impact statements to address these issues in the planning phase. Energy efficiency should also be incorporated into the planning and design processes wherever there are direct or indirect impacts on energy use such as in the design of industrial facilities or in transportation planning.

There is a role for both bilateral aid organizations and for a variety of international organizations to play a very active role in promoting all of these endeavours. The energy lending of the World Bank and the regional banks has evolved from support for energy (especially electricity) supply projects to improved energy efficiency of these projects. It is slowly evolving to include end-use efficiency as well. A major impediment to end-use energy efficiency loans in developing countries is the lack of strong organizations and trained professionals to design and carry out the projects. The lending agencies, working with other bilateral and multilateral aid agencies, could establish programs that would greatly enhance the institutions and human resources devoted to energy efficiency in developing countries. Such co-operative ventures, among developing countries, international loan agencies, and aid agencies in industrialized countries, could overcome many of the barriers existing within developing countries to implement large-scale energy efficiency programs.

Finally, **joint implementation** (JI) involves a bi-or multi-lateral agreement, in which (donor) countries with high greenhouse gas abatement costs in implementing mitigation measures in a (host) country with lower costs, and receive credit for (part of) the resulting reduction in emissions [Pearce,1995]. The rationale behind JI is that it would lead to more cost-effective emission reduction. Current JI projects mostly involve CO_2 fixation (reforestation), fuel switching (in Eastern Europe) and, still limited, transfer of renewable energy or energy efficient technologies (for example the ILUMEX project between Mexico, Norway and The World Bank [Luzuriaga,1995]). More energy efficiency projects are being studied (e.g. by the NORDIC [Nielsen,1995] and the Japanese JI Project).

JI is also associated with many problems [Jepma,1995]. The concept of JI assumes that it is possible to identify countries with lower abatement costs, which is not always clear, as a large range of cost effective options exist in industrialized countries [Jackson,1995]. Comprehensive analyses of abatement options are nearly non-existent for many countries. Also, it is argued that the transaction costs for JI projects might be higher than for domestic projects, and hence make JI less cost-effective. The main problems with JI are associated with responsibility and national obligations, e.g. industrialized countries 'offload' [Pearce,1995] their problem onto other (mainly developing, but also economies-in-transition) countries (decreasing the responsibility of donor countries while reducing cost effective options of host countries themselves) and use JI as a substitute to technology transfer (as obligated in the FCCC) and development aid. Advocates of JI see it as a means to increase technology transfer to DCs, and to involve private capital in development. A pilot phase to test and evaluate JI projects, as decided by the Conference of Parties, is needed. In this phase the issue of crediting still remains unsolved. To be successful JI project should fit in the scope of sustainable development of the host country (without reducing national autonomy and with cooperation of the national government), have multiple (environmental) benefits, not replace development aid, be selected using strict criteria and be limited to a (small, e.g. 15%) part of the abatement obligations of an industrialized country (the most likely donors). Determination (and crediting) of the net emission reductions is also a problem that stresses the need of well-developed baseline emissions, e.g. emissions that would occur in the absence of the project. JI is not straightforward. It can prove to be a viable financing instrument to accelerate developments in economies-in-transition and in developing countries, but only if implemented according to the criteria discussed above. Comprehensive evaluation of the pilot projects is necessary to formulate and adapt these criteria.

4.5 Conclusions

A wide range of barriers exist that delay implementation or development of energy efficiency measures. A variety of policy instruments has been developed in various countries, and new instruments are developed to meet the challenges of the changing energy market. The discussion shows that it is necessary to integrate instruments to have the most effective impact [Geller and Nadel,1994], and tailor the policy strategy and instrumental mix to the various actors and sectors.

Considering the huge growth of energy consumption expected in developing countries, enhanced efforts are needed to improve cooperation between industrialized and developing countries. Strategic choices of national governments and international organisations are necessary to develop policy mechanisms enhancing the role of efficiency improvement.

5. Conclusions and Recommendations

This report provides an assessment of opportunities for energy and material efficiency improvement. Energy and material use are central to social-economic and environmental development. While energy is an important economic driver, it is also one of the major sources of environmental pollution. Energy and material efficiency improvement are generally seen as the main means to substantially reduce or curtail negative environmental impacts. The extent to which energy and material efficiency potentials are met will depend on the successful implementation of policies within countries themselves, as well as development of suitable frameworks in an international context.

5.1 Conclusions

In this assessment we focus on energy because of the important environmental and social implications of its use. The study has shown that large potentials exist for energy savings through energy and material efficiency improvement in all sectors of society and that these savings can change current unsustainable consumption patterns. Considerable energy savings have been achieved in recent decades. Three factors have played a major role in this development: increasing energy prices (except for the past five to ten years), energy policies aimed at bringing energy efficiency into the market, and technological development.

Energy and material efficiency improvement reduces air pollution (global warming, acid precipitation, and smog in the urban and industrial environment), waste production (ashes, slags), and water and thermal pollution. Efficiency improvement is a cheap energy source. Other economic benefits are the reduced costs of energy transformation and generation, reduced fuel imports, and increased energy security. Technologies do not now, nor will in the foreseeable future, provide a limitation on continuing energy efficiency improvements.

To analyse opportunities to the year 2020 we developed three scenarios, partly based on a previous study performed by members of the research team [WEC,1995a]. Under business-as-usual conditions, energy consumption will grow at an estimated average rate of 2.0%/year to 566 EJ between 1990 and 2020. Important growing energy markets are the developing countries, especially in the industrial sector and in energy use for buildings. Energy use for transport is expected to increase globally. Direct energy consumption in agriculture, although small, will also grow in developing countries and remain nearly constant in the industrialized countries. Two scenarios were developed to reflect different development paths for energy policy. Under a state-of-the-art scenario (assuming adoption of today's state-of-the-art technology in all sectors by the year 2020) energy use will still grow, but limited to 1.3%/year to 465 EJ in 2020. The strongest growth will be found in buildings and transport. The advanced technology/ecologically driven scenario assumes active energy policies that lead to accelerated implementation and development of new energy-efficient technologies. Under this scenario, growth of global energy use can be limited to 0.6%/year to 373 EJ, with slight growth in buildings, agriculture and transport, and nearly constant energy use in the industrial sector.

In these scenarios material efficiency improvement, with exception of recycling, has not yet been incorporated. We estimate that increased material efficiency improvement, in addition to energy efficiency measures, may decrease the growth rate of energy consumption to 0.2%/year, resulting in an energy consumption of 334 EJ under the 'advanced technology' scenario. The scenario results are presented in Figure 5.1.

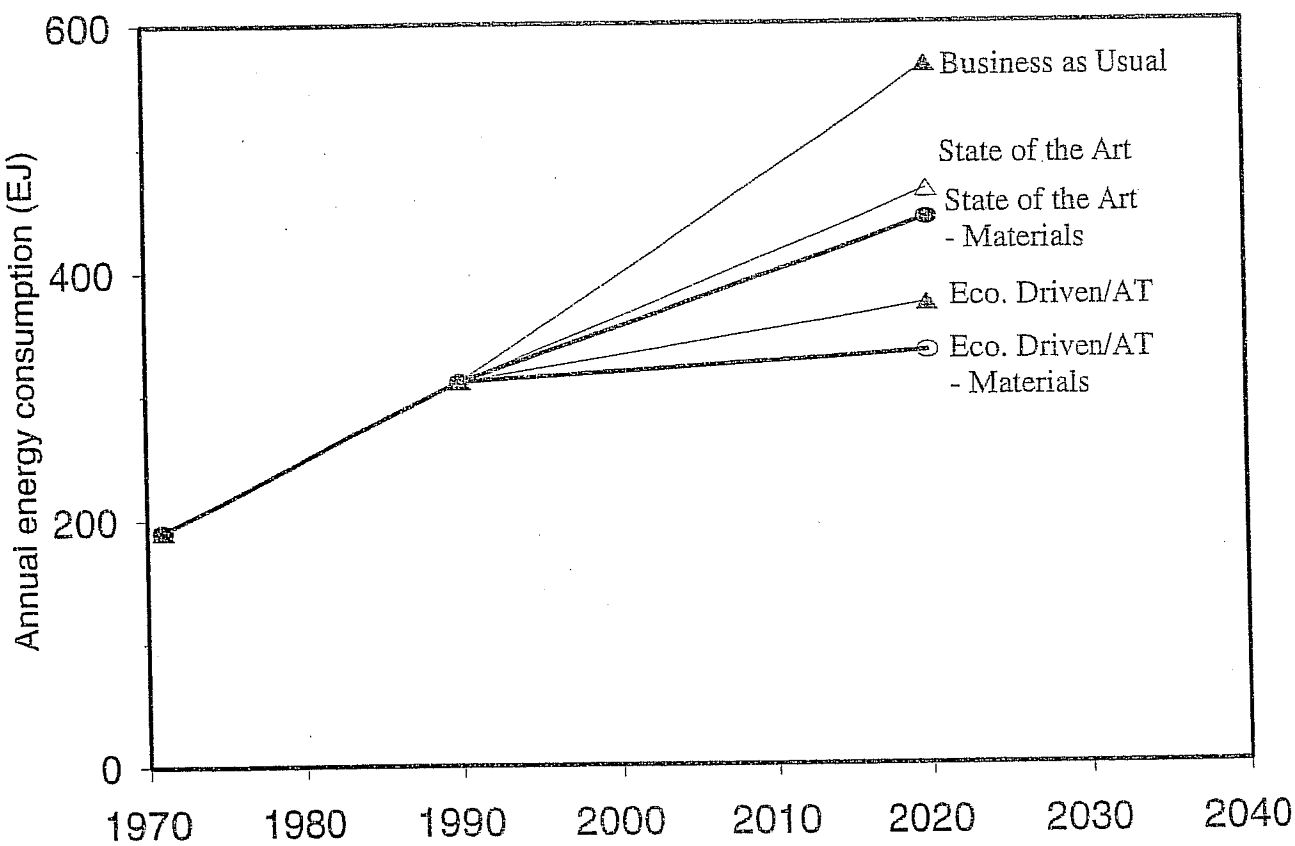

Figure 5.1 Results of the three scenarios for aggregate world energy consumption between 1990 and 2020. The standard lines depict energy efficiency scenarios. The thick lines represent scenarios with energy and material efficiency improvement.

The energy and material efficiency improvements in the two efficient scenarios will not be realized without a significant increase in policies using new and innovative combinations of instruments. Our review of current energy policies and instruments showed that energy is often still seen as a supply side issue, especially in developing countries and in the allocation of R&D budgets in industrialized countries. However, large differences exist between regions and countries. For example, in Africa most energy policies and expenditures are related to expanding energy supply while in some rapidly industrializing countries in Asia energy efficiency improvement has become an important element of energy and economic policy.

Barriers to efficiency improvement can be summarized in five categories: unwillingness to invest, lack of available and accessible information, economic disincentives, and organizational barriers. The degree in which a barrier limits efficiency improvement is strongly dependent on the situation of the actor (households, small companies, large industries, utilities). This means that no single instrument will 'do the job'. A range of policy instruments are available, and innovative approaches or combinations have been tried in some countries. Successful policy can contain regulation (e.g. product standards) and guidelines, economic instruments and incentives, voluntary agreements and actions, information, education and training, and research, development and demonstration policies. Successful polices with proven track records in several sectors include efficiency standards and codes, technology development, and utility/government programs and partnerships. Improved international cooperation to develop policy instruments and technologies to meet developing country needs will be necessary, especially in light of the large anticipated growth in this region. New instruments, e.g. joint implementation, are under development, but comprehensive evaluation is needed to tailor these instruments to specific needs.

Material efficiency improvement has not yet received as much attention in policymaking and analyses as energy efficiency. As a result, detailed data on the qualities and quantities of final consumption are not available, making it difficult to formulate effective policies. However, the available studies suggest the existence of large potentials for improved use of many materials in industrialized and developing countries. Efficiency improvement in industrialized countries can reduce consumption up to 40% for some materials, maintaining the same service level. Many options for material efficiency improvement exist. Despite the growing demand for services in developing countries, possibilities exist to reduce the material intensity of these services. Integrated assessments of the energy/materials-system suggest that energy savings can be achieved at lower costs through combined energy and material efficiency approaches. Current initiatives to develop clean technologies and products show that these can be successfully combined to achieve large reductions in resource inputs and emissions. The change to less energy-intensive consumption patterns should also result in reduced consumption of materials. As with energy, there are barriers to material efficiency improvement which, along with the problems mentioned above, include issues related to chain management such as communication and linking of material-product-waste streams.

5.2 Recommendations

A policy aimed at sustainable development places energy and material efficiency improvement in the middle of the economic and environmental policy field. Energy efficiency facilitates the introduction of renewables and 'buys time' for the development of low-cost renewable energy sources. However, energy efficiency does not receive attention appropriate for the important role it needs to play in development of an environmentally-sustainable society in current energy policies in industrialized and developing countries. Regulatory frameworks typically do not recognize energy efficiency improvement as an energy source. A balanced approach is required to place supply and demand on an equal footing. Radical changes are needed to fulfil the promise of energy efficiency and to fulfil energy needs more sustainably, accounting for social, economic and environmental issues. Below we present a number of recommendations formulated on the basis of our study, which we request to be considered, as appropriate, by all States, entities within the United Nations system, other inter-governmental and non-governmental organizations.

1. **Cooperation** in the energy efficiency field should be increased between the industrialized countries and the countries in the developing world and economies in transition. Without such cooperation and assistance lower energy paths (as reflected in the state-of-the-art and advanced technology-scenarios in this paper) are not possible because so much of the world's energy growth will be in developing countries. Cooperation should first be directed at building public awareness and indigenous capacity (see below) which is one of the basic steps in development and in increasing energy and material efficiency. Such awareness will lead to an increased focus on sustainability issues and can have long-term effects on policy formulation and effectiveness.

2. **Capacity building** includes education, training, and information transfer on the national and international level. Training in all aspects of energy and material efficiency is essential, ranging from energy planning to technical and engineering training. An analysis of the information and training needs should be executed. The efforts should be evaluated regularly to be able to redirect the programmes to the needs.

3. There is a need for detailed **information** regarding technical options for energy and material efficiency improvement for use in national policymaking as well for development of international initiatives. However, this information often is not available or accessible. This is especially true for developing countries which typically have more limited knowledge, information, and education resources. The quality and availability of information on energy and material efficiency provided through governments, energy agencies, vendors, trade and consumer associations, or other appropriate bodies needs to be improved. The training and information structure should be tailored to meet the demands of the energy customer. Continuous efforts are needed to maintain effectiveness, as knowledge infrastructure is difficult to build up but easy to break.

4. Because of the expected high economic growth rates in **developing countries**, huge investments in industrial production equipment and energy infrastructure which will determine the structure for the next decades or even longer are expected. These upcoming investments represent an opportunity, if acted on appropriately, to adopt the best available technologies, as these growing markets are good theatres for innovation. Tariffs and other barriers for importing and exporting energy-efficient technologies should be removed to

enhance technology transfer. The emerging markets for new (and clean) technologies in developing countries stress the importance of considering the special demands these markets put on product and process development. Developing technologies that enable production and implementation in these countries can help these countries to 'leapfrog' the unsustainable development path followed in the past by industrialized countries. This includes demonstrating the feasibility of advanced technologies in developing countries.

5. Countries should establish **comprehensive policy plans** with clearly defined energy and material efficiency goals. Such plans set clear targets for all actors and make it possible to direct and evaluate policies. In addition, clearly defined goals improve communication, credibility, and the outlook for investors. A medium-to long-term perspective on energy polices will reduce perceived risks. The effectiveness of comprehensive policies is illustrated by countries such as South Korea and Japan. To be effective, the policy plans should contain 'hard' goals. The UN could play an important role in overseeing and harmonizing policy plans, as well as the achievements (as set forth in the FCCC).

6. Development and design of new **regulatory, legal, and market frameworks** is needed because current frameworks do not fully recognize the role of energy efficiency improvement, both nationally and internationally. Important global changes and developments are taking place in the power sector, leading on one hand to larger multi-national utilities, and on the other hand to development of decentralized power generation by self generators and utilities. A new regulatory framework should emphasize internalization of input and emission reduction through integral environmental auditing and development, rather than end-of-pipe measures. This can be accomplished through introducing integrated resource planning, demand side management, and attention to generation technologies like cogeneration and various renewable energy sources. The establishment and strengthening of the role of energy service companies (or utilities) in developing countries can be an important step towards generating long term interest in efficiency improvement.

7. Mechanisms for energy and material efficiency improvement are not limited to technologies. This is because a number of technical, socio-economic, and behavioral **barriers** limit the market diffusion and correct application of new energy-efficient technologies. The barriers are not yet fully understood and are partly due to the issues raised above. A better understanding of the barriers, in order to formulate efficient policy instruments and incentives is needed.

8. With regard to implementation strategies is there **no 'deus ex machina'**; instead, an integrated set of policy instruments accounting for the characteristics of technologies and target groups addressed is needed.

9. Subsidized **energy prices** in many countries provide disincentives for energy efficiency improvement or efficient use of materials. Removal of existing energy subsidies must be

done carefully to take account of social and economic circumstances, as energy is essential for development. Price transformation should take place within a strict schedule, while mitigating the negative effects for the poorest by special efficiency programmes. Important incentives for energy and materials efficiency will be provided with the establishment of energy prices that reflect real costs, internalizing factors now external to the pricing structure (e.g. environmental and social costs). Recognizing that no consensus is yet reached on this issue, planned step-wise price increases are needed as an incentive for energy efficiency improvement, which will also reduce the perceived uncertainty in energy price developments by investors.

10. National and international **standards** for many products (e.g. appliances, packaging, buildings) and production equipment (e.g. electric motors, boilers), and internationally accepted testing procedures have played an important role in improving the environmental characteristics of these products and processes. Standards are likely to continue playing an important role and widespread adoption and adaption over time is recommended to push technology development. A legal basis should be provided for product standards (e.g. energy standards for appliances) in national legislation. Standard setting along with technology procurement programmes will strengthen R&D. Standards play a role in establishing widespread 'uniform' technologies or practices. New forms and applications of efficiency standards should be investigated. Establishment of internationally accepted testing procedures would be an important step to assist developing countries willing to promote standard setting.

11. **Financing and fiscal instruments** have taken various forms (e.g. subsidies, accelerated depreciation). An important hurdle to energy efficiency investments seems to be the different financing criteria for supply and demand options. Capital allocation should use life-cycle costing for demand options or make use of innovative approaches (e.g. by energy service companies or utilities). Financial and fiscal incentives should be tailored to the markets in which the actor is operating, potentially reducing the 'free-rider' problem. In line with the above, financing or fiscal incentives for end-of-pipe technologies should be phased out to strengthen the process of internalization and integrated resource planning in design of processes, products, and infrastructures. Internationally, accessible and affordable financing for developing countries is needed, e.g. by redirecting international or multilateral development funding to efficient (and renewable) energy technologies. A considerable part of the energy lendings of such organisations, e.g. the World Bank, should be spend on energy efficiency within the next years. Technology procurement programmes by utilities or government can play a role in deepening the cooperation between the actors, which can take the form of organized competitions.

12. **Voluntary agreements** or covenants are currently being used to pursue energy efficiency or technology development goals in several countries. This instrument is useful to establish a concerted negotiated goal, improve partnerships between the actors, and may improve the economic efficiencies of achieving this goal. Evaluation of the effectiveness is not yet feasible, but preliminary data suggest that voluntary agreements can be effective, but should

always be accompanied by other instruments. The viability of voluntary agreements in international policymaking should be investigated.

13. Energy efficiency improvement has a large potential in the medium and long term, and is generally seen as the major driver to reduce environmental impacts and reconstruction of the energy system. However, OECD **energy RD&D budgets** designate only 7% for energy efficiency improvement, while over 90% is spent on supply side technologies (mainly nuclear power, 54%) [IEA,1994]. Reallocation of RD&D budgets is needed to better reflect the importance of efficiency improvement. International collaboration, where RD&D efforts among countries are aligned, can be an important means to improve the efficiency and effectiveness of RD&D programmes.

14. To improve effectiveness, there needs to be well-established and **accepted analysis and monitoring instruments** to evaluate and redirect policies and instruments to changing conditions and situations. (Inter-) nationally accepted analysis methodologies can help to identify the most effective options and policies in different situations, and hence increase the effectiveness of international cooperation initiatives like technology transfer, development aid, or joint implementation. Assessment of the options for energy efficiency improvement should be done using a common harmonized bottom-up analysis methodology, enabling international comparison of energy efficiency and improvement options and strategies. Emphasis should be on analysis starting from the specific end-uses, potentials, and costs. There is a critical need for detailed and good quality data collection, publication and analysis. It should be noted that relatively little knowledge is available with respect to end-use of materials and products and the possibilities to change to more material efficient and sustainable consumption patterns.

15. With regard to the individual sectors assessed in this study some specific recommendations can be made. In **industry** R&D stimulation is very important, as energy efficiency improvement has often been part of technological progress. Innovation can also be accelerated by improving implementation rates of innovative environmentally-sound technologies. In **buildings**, standards and codes (for appliances and buildings) have been shown to be the most effective instruments. A policy of gradually increasing standards should be set to give a clear signal to the builders and manufacturers (R&D). It is important to set out policies along these lines today, because of the long life-time of buildings, and because renovating for energy efficiency of buildings is more expensive than construction. In **agriculture** energy efficiency is strongly dependent on direct and indirect energy inputs. Sustainable energy policies in agriculture should therefore aim at minimizing the inputs and environmental impact relative to the output in an integrated way. With regard to **transport**, important infrastructural choices made today will lay out the transport needs and means in the long term. Transportation policies should therefore aim at influencing this infrastructure in a way that integrates all social needs incorporated in meeting transportation demand. Such an approach is likely to lead to reduced energy requirements for the desired transport services. Regional planning in developing countries presents a particular challenge and

opportunity because of rapidly expanding transport infrastructures. Development of inherent clean transportation modes is important due to the wide range of problems associated with transport (e.g. energy use, pollution, dependence on one energy carrier, congestion, land use). Development could be accelerated by setting appropriate standards for automobiles, and by introducing policies that promote the introduction of 'clean' vehicles.

16. The United Nations can play a vital role in the transition towards more sustainable development. The role of the UN can be strengthened by improving the importance of energy and material efficiency, by improving the exchange of information on these activities, capacity building within the UN system, and improving the programme coordination. Although improved use and recognition of the existing regional commissions, programmes (e.g. UNDP), and Division for Sustainable Development is essential, the establishment of a dedicated institution for issues related to energy and material use could be studied as well. The UN could play a more important role in the organization of international activities proposed above. This should encompass, first of all, establishing an initiative for training and investigating the needs for information and training in developing countries. Secondly, the UN should play a role in the harmonization of analysis and testing methodologies, enabling developing countries and the international community to improve the efficiency of policy and technology needs. Thirdly, the UN should play a major role in re-directing international capital spending (e.g. World Bank, EBRD, GEF) into directions in line with the recommendations presented above.

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