5 Potentials for the Sustainable Development of Energy Systems

5.1 Introduction

As we have seen in the previous chapter, the use of fossil energy is a source of environmental damages and risks. Energy use in the European Union is 4.5 kW per capita (see Fig. B1, Appendix to chapter 4), which is beyond levels that can be called sustainable. Of the environmental risks, the possibility of climate change through the emission of carbon dioxide is a prominent one. Greenhouse gas emissions in the European Union are 10.5 t carbon dioxide equivalent per capita per year. According to the present understanding, emissions of carbon dioxide need to be strongly reduced, at least in industrialized countries.

There is already a wide range of technologies available to reduce energy-related emissions of carbon dioxide. Existing technologies can improve the efficiency of energy production and consumption by 20–40% in one or two decades. Important options are, for instance, the extension of the application of building insulation, the use of building management systems, the optimization of electric appliances, the application of combined generation of heat and power (CHP), the further improvement of car engines and aerodynamics, and a large set of adaptation options for industrial processes. Another option is a shift from coal to natural gas. Also, renewable energy sources can already play a limited role in the coming decade. Such options are available and are sufficient to reach short and medium term targets, like those set by the Kyoto protocol for the period 2008 to 2012 (K. Blok, D. de Jager, C.A. Hendriks: Economic Evaluation of Sectoral Objectives for Climate Change – Summary for Policy Makers, European Commission, DG Environment, 2001).

Reaching longer term targets, like those for a period of 30–100 years ahead requires not only the further adoption of the technologies mentioned, but also the application of new technologies. These technologies should be adopted at a rate that at least compensates for the increase in human activities associated with economic growth. The aim of this chapter is to investigate whether a more sustainable energy system is feasible. To this end, technologies that are important for the longer term on the road towards a more sustainable energy system will be evaluated and their possible role for the European Union will be quantified.

Production	Conversion	Transport Storage Distribution	End-use conversion	End-use
e.g. coal mining wind turbines natural gas prod.	e.g. refineries power plants	e.g. oil storage electricity grids	e.g. boilers combined-heat-and-power-plants	e.g. space heating cooking lighting

Table 5.1 Schematic description of the stages of an energy system (see also chapter 2, Box 3)

An energy system can schematically be broken down into five stages (see table 5.1). Energy is produced from natural resources, often converted into other energy carriers and subsequently transported and distributed to the so-called final consumers. The amount of energy that is used by final consumers is called final energy use. The final consumers can convert the energy further and finally use it for a wide range of applications.

In this paper, we will focus on two categories of options: energy efficiency improvement and substitution (see chapter 4). First, we will discuss energy and material efficiency improvement options that exist in end-use and conversion (section 5.2). Next, renewable energy options will be covered (section 5.3). Note that the aim of this paper is just to present some overall lines, illustrated with some specific examples. More extended analysis can be found in the literature (K. Blok, W.C. Turkenburg, W. Eichhammer, U. Farinelli, T.B. Johansson (eds.): Overview of Energy RD&D Options for a Sustainable Future, Office for Official Publications of the European Communities, Luxembourg, 1996. Federal Energy Research and Development for the Challenges of the 21st Century, President's Committee of Advisors on Science and Technology (PCAST), Washington D.C., 1997).

On the basis of these analyses, some images are presented and the prospects for a sustainable energy system in the long term will be discussed (section 5.4). Finally, an overview will be given of barriers for the materialization of the technological potentials (5.5).

5.2 Technical energy efficiency improvement

Traditionally, the energy efficiency of energy use improves by about 0.5–2% per year, with the higher rates occurring in periods with high fuel prices or active energy policies. In this section the feasibility of enhanced energy efficiency improvement will be discussed.

First of all, some more need to be said about what is meant with technical energy efficiency[1] improvement. Technical energy efficiency is output divided by input of

[1] Here the attribute 'technical' is added to distinguish it from the (overall) energy efficiency defined in Chapter 4 (Box 4.1) as GDP per energy consumption of a country. Where the context is clear, the adjective 'technical' is omitted.

a process in which energy is an input. The opposite of energy efficiency is input divided by output, often indicated as the specific energy consumption. If this chapter talks about energy efficiency improvement, always a decline of the specific energy consumption is meant.

In this section, opportunities for technical energy efficiency improvement in the three major end-use sectors: manufacturing industry, residential and commercial buildings, and transportation will be discussed.

Manufacturing industry

The opportunities for future energy efficiency improvement for a number of sectors in heavy industry were analyzed by De Beer[2]. This was done according to a structured method, including: (i) process and energy analysis; (ii) technology identification; (iii) technology characterization. The results of this work provide for an overview of the potential for energy efficiency improvement for selected sectors in manufacturing industry, see Table 5.2. We see that in all the cases it is possible to bridge about half of the gap between the present best technologies and the thermodynamic minimum with identified new technologies. Despite the extended inventories that were made, all identified technologies could be commercialized well within 30 years, and the overwhelming majority even within 15 years. However, actual development of new industrial process technologies is a slow process (E. Luiten: Beyond Energy Efficiency, Ph.D. Thesis, Utrecht University, 13 September 2001); autonomous development alone will not lead to the development of these technologies within these timeframes.

It is clear that in a number of these cases the further decrease in specific energy use is limited by the thermodynamic minima that exist for certain conversions. However, in addition the energy demand for producing these materials can be further limited by using primary materials in a more efficient way. This can be done through:

– more material-efficient product design;
– material and product recycling;
– material cascading;
– material substitution, including the use of biomass-derived materials.

Some studies have shown that with existing technology substantial improvement in material efficiency is possible, both for individual products ('eco-design') and for integral material systems. However, long-term prospects are still unknown and certainly not quantified. It is not unlikely that – as is the case with energy efficiency – also in the case of material efficiency further innovations seem possible, including the development of new materials; alternative inputs and processing routes for existing materials; tools for the development of material-efficient products; and improved material recycling through the use of material recognition systems, better separation techniques and new logistic systems.

[2] J. de Beer: Potential for Industrial Energy-Efficiency Improvement in the Long Term, Ph.D. Thesis, Utrecht University, 1998. Parts of this thesis are also published as: J. de Beer, E. Worrell, K. Blok: Future Technologies for Energy-Efficient Iron and Steel Making, Annual Review of Energy and Environment, **23**(1998)123-205; and: J.G. de Beer, E. Worrell en K. Blok, Long-term energy-efficiency improvement in the paper and board industry, Energy, the International Journal, 23(1998)21-42.

Table 5.2 Overview of present best technologies, and identified potential for improvement in terms of specific energy consumption (in GJ/t) for some industrial energy functions.

	Specific energy consumption levels (GJ/t)			Relevant future technologies
	Present best technology	Thermo-dynamic minimum	Combination of best identified future technologies	
Paper/board (paper drying)	2.3–8.6	0.0	0.6–4.3	Impulse drying Condebelt Dry sheet forming Airless drying
Primary steel production	19.0	6.6	12.5	Smelt reduction Strip casting
Secondary steel production	7.0	0.0	3.5	Combination shaft furnace Strip casting
Ammonia production	33.0	24.1	28.6	Membrane reactors
Nitric acid production	26.8	3.2	15.3	Gas turbine or solid-oxide-fuel-cell integration

Residential and commercial sector

Space heating and hot water production are important energy functions in buildings and responsible for about two thirds of primary energy demand. The developments for these energy functions can be illustrated by the developments for the residential sector in the Netherlands where the average energy use for space heating and hot water production was about 100 GJ (~ 1 GJ/m^2) per year in the late seventies, both for the average stock and for new buildings. At present the energy use for the average stock has declined to 70 GJ per year (R.J. Weegink: Basisonderzoek Aardgas Kleinverbruikers BAK 1997, EnergieNed, Arnhem, 1998). For new dwellings a standard was set in 1996 that forced building developers to build houses with a projected consumption of about 44 GJ. This was further decreased in two steps to 32 GJ in the year 2000.

Meanwhile, five real estate developers built a total of 200 buildings reaching a level of 19 GJ (completed in 1999–2000). This was achieved by expanding insulation, the application of heat recovery systems and the use of solar hot water heaters.

This is not the end of the possibilities. New technologies can be developed, like:

– the use of new insulation materials (notably the use of vacuum insulation);
– further reduction of the heat loss through windows;

– the application of heat pumps (instead fuel cells may play a role as heat source, also[3]);
– compact energy storage systems (making solar space heating possible).

In the end this technical developments could make it possible to build houses with zero energy use at affordable costs.

Transportation

Passenger cars are responsible for about two-thirds of energy use for transportation. During the nineties the energy use of passenger cars in the European Union was about 7 – 8 liters per 100 km (both for new cars and for the average). The prospects are good for a further decrease of specific energy use (see Table 5.3). Some Japanese manufacturers are already on the market with hybrid vehicles, combining a conventional engine and an electric motor. A step further would be the use of proton-exchange-membrane (PEM) fuel cells in cars, although it might be that the optimized hybrids will prove to be more efficient at the end (M.A. Weiss, J.B. Heywood, E.M. Drake, A. Schafer, F.F. AuYeung: On the Road in 2020, Energy Laboratory, MIT, Cambridge, MA, USA, 2000). There are even suggestions that applying new light materials, in combination with the new propulsion technologies, may bring fuel consumption levels to about 1 liter of gasoline-equivalent per 100 km (E. von Weizsäcker, A.B. Lovins, L.H. Lovins: Factor Four, Earthscan, London, 1998).

Table 5.3 Specific energy use of passenger cars (liter gasoline-equivalent per 100 km)

Present average in Europe	7–8
European standard 2008 (average new)	5.8
Hybrids on the market	4–5
Improved hybrids or fuel cell cars	2–3
Ultralights	0.8–1.6

Energy efficiency improvement of energy conversion

Energy use and energy conversion exists in many parts of the energy supply system. The most important conversion losses occur in the electricity sector, where worldwide only about one third of the fossil fuel input is converted to electricity, with a typical conversion efficiency of 40% in the most efficient countries.

Much higher efficiencies are possible already. Natural-gas fired combined-cycle power plants can be built with a conversion efficiency of nearly 60% by now, whereas the best coal-fired power plants reach somewhat more than 45%. The energy efficiency increase for natural-gas fired systems was most prominent in the past decades, mainly caused by a tremendous performance increase of gas turbines.

[3] These options are not better than the present best technology (combined-cycle district heating) but more widely applicable, see: M.E. Ossebaard, A.J.M. van Wijk, M.T. van Wees: Heat Supply in the Netherlands: A Systems Analysis of Costs, Exergy Efficiency, CO_2 and NO_x Emissions, Energy 22(1997)1087-1098.

The expectation is that further improvement is possible, but the limitations are in sight: the maximum theoretical efficiency of an energy conversion process based on combustion is 70–75%.

The best-known example of an electricity production process not based on combustion is the fuel cell. Fuel cells are under development since many decades, but for stationary applications they have been ‘locked out’ by the rapid development of the gas turbine technology. It might be that, for instance, solid oxide fuel cells in combination with combined cycle plants may be able to reach conversion efficiencies above 70%[4].

The effect on carbon dioxide emissions can be even more pronounced than those on efficiencies. In 1995, the average emission factor for fossil-fuel based power generation in the European Union was 790 g CO_2/kWh (Derived from IEA Energy Statistics). For natural-gas based power generation with an efficiency of 70% the emission factor drops to 290 g CO_2/kWh.

Overall effects of enhanced development of energy efficient technology

The sectors of energy consumption discussed here together cover about half of the energy use in most industrialized countries. For each of these sectors we have identified options that make it possible to decrease specific energy consumption levels for *new* equipment at substantial rates, i.e., 5% per year or more. Although a 5% per year decline for new equipment is very substantial (if maintained for 50 years, this would be a decline by more than 90%), the effect on the *average* energy efficiency is limited due to the slow turnover of capital stock.

To analyze this effect a simple vintage simulation model was developed. In all cases the growth of the stock of energy using equipment is assumed to be 2% per year. In the reference case, an energy efficiency improvement of 1.5% per year for *all* equipment is assumed, leading to an increasing energy demand (see fig. 5.1, dotted curve). The reference case is compared to simulations in which an enhanced rate of energy efficiency improvement of 5% per year for *new* equipment is assumed for 80% of the energy applications (which, in fact, corresponds to a mean rate of 4.3% per year for all the applications). No effect of retrofit of equipment is taken into account, as this is relatively unimportant for the long term.

First, the effect of the average service life of the replaced equipment is examined:

- 15 years: typical for cars and household appliances;
- 30 years: typical for large-scale industrial process equipment and power plants;
- 60 years: typical for buildings.

The results are depicted in figure 5.1. The baseline shows an increase in energy use by about 25% in 50 years. In the enhanced energy efficiency improvement cases the energy use *decreases* by approximately 50% until 2050, except for the equipment with a service life of 60 years, for which the energy use decreases by only one third.

[4] PEM fuel cells may be important in transportation or small-scale combined generation of heat and power, see section 2.

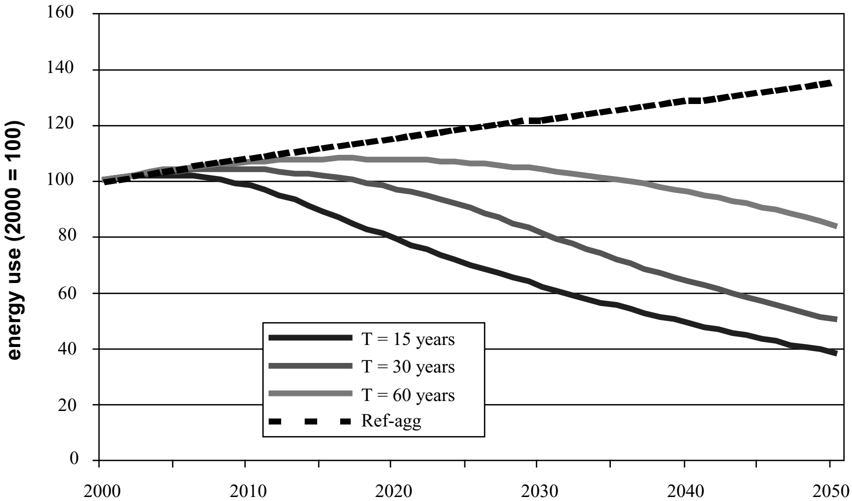

Fig. 5.1 Development of energy use for different service lifespans T of equipment, assuming that since 2000 the specific energy use decreases by 5% per year for 80 % of the new equipment. In the reference case the improvement rate for all equipment is 1.5% per year (dotted line). In all calculations an increase of energy using equipment of 2% per year is assumed.

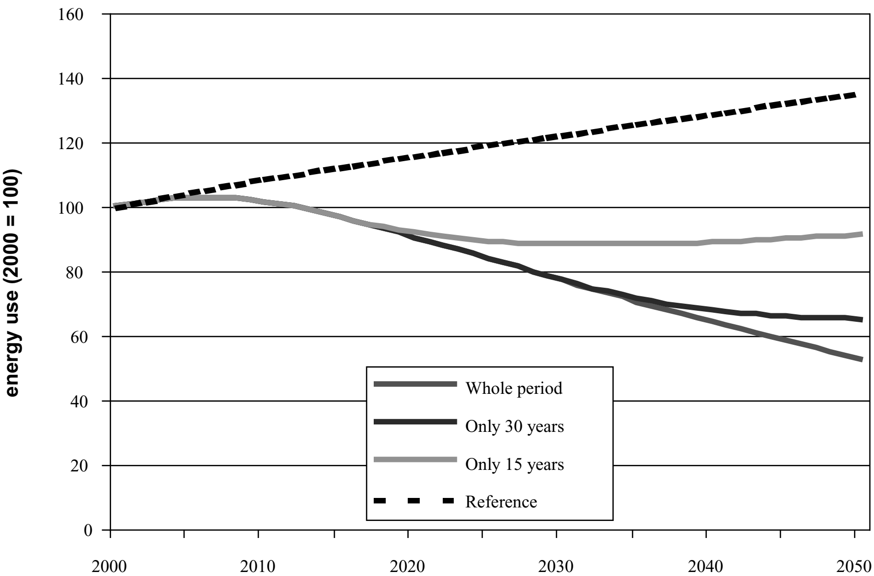

Fig. 5.2 As in fig. 5.2 with the additional assumption that the enhanced rate of energy efficiency improvement will only materialize for a limited period (i.e. for 15 years, for 30 years and for 50 years). The equipment has a mix of lifetimes (50% 15 years, 25% 30 years, 25% 60 years). Reference case (dotted line) as in fig. 5.2.

Next, it is assumed that the rapid rate of innovation can be maintained only for a limited period, i.e. 15 or 30 years. The results given in figure 5.2 show that even then the long-term effects are still in the range of 20 to 40%. From this analysis we conclude that in the long run the effect on final energy use of an accelerated rate of energy efficiency improvement can be very substantial, even if such accelerated rate is only maintained for 15 years.

5.3 Renewable energy sources

Energy can be covered from a variety of sources. Box 1 gives an overview of the possibilities of the various sources. For a sustainable energy system, the application of renewable energy sources seems most appropriate.

Renewable energy already contributes 12–16% to the (commercial and non-commercial) global energy supply, mainly as traditional biomass and large-scale hydropower (see Appendix of chapter 4, fig. A.2). Various scenario studies indicate that in the second half of the next century half of the world energy demand can be covered from renewable sources (T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams (eds.): Renewable Energy – Sources for Fuels and Electricity, Island Press, Washington, D.C., 1993; World Energy Assessment, UNDP/UNDESA/WEC, United Nations Development Programme, New York, 2000 (Chapter 7)).

In the following, different renewable energy options are discussed: biomass, wind and solar. In this section we focus on the options for Western Europe. A summary of all relevant energy resources is given in bx 5.1.

Biomass energy

Biomass is a generic term for all forms of energy derived from the biosphere (mainly plants), in a non-fossil form. Wood is the best-know example. At present wood is the most abundantly used renewable energy source and the most important source of energy for a large part of the world's population.

An important source of biomass is organic waste, e.g. domestic waste, manure, household and industrial wastewater, agricultural crop residues, residues from forestry. The estimates for the availability of residues in Western Europe range from 4–5 EJ (Pimm (2001)), which is somewhat less than 10% of present energy demand.

Next, biomass can be cultivated especially for energy purposes. Apart from wood, one can also think of a range of other crops, e.g. sugar cane, eucalyptus, sweet sorghum, miscanthus and sugar beet. For energy purposes, the productivity in terms of dry mass per hectare is important. For most biomass crops, where water availability is not a limiting factor, the productivity ranges from 10–30 t of dry matter per hectare; it depends on the type of crop, soil conditions and climate. Especially in arid regions productivities can be substantially lower, down to 2–4 t per hectare. For Europe, average yields are 10–12 t of dry matter per hectare. For the future, these values may increase, maybe to 15 t per hectare for the best soils.

Of course, the energy production depends on the area of available land. Table 5.4 gives an overview of land area in the European Union. In order to produce 6 EJ

Box 5.1 Possible energy sources for tomorrow's global energy system

The World Energy Assessment (Energy and the Challenge of Sustainability. World Energy Assessment, UNDP/OECD/WEC, 2000), which was published some years ago, gives a comprehensive overview of all energy resources presently known. It is very difficult, for various reasons, to predict the future potential of these options for the next 50 years. For instance, how would one quantify the potential of photovoltaic energy, considering the immense solar energy flux (see Chap. 2, Box 2)? The following considerations aim not so much at the theoretical potential of certain energy resources; they are rather based on an assessment whether a substantial share of the total demand of 600 to 1,000 EJ/year (20 to 25% of which as electricity) to be expected in 50 years can then be met by one particular resource, and what this would imply.

1. **Fossil energies:** Regarding the existing resources it would be quite possible, according to Tab. 4.3, that fossil energies still contribute the largest share to the global energy system in 2050. Yet this would entail the exploration of unconventional oil and gas deposits and/or a return to coal. Table 4.5 gives an overview of the consequences of this new strategy for the CO_2 system.
2. **Nuclear energy** (from fission and, in principle, from fusion too); *non-renewable*, but factually limitless with the technologies fully developed (reprocessing, breeders and, finally, fusion reactors), though only practical in a world that can be completely controlled politically. For instance, the present stock of power plants would have to grow 15- to 20-fold to make nuclear energy the main column of the future energy system. As explained in Chapter 4.2.4, the chances for this development are considered small.
3. **Hydropower;** *renewable*. Global capacity could be expanded to about 30 EJ/yr (today: 9.3 EJ/yr) in an economic way, and even to 50 EJ/J limited by technology only. However, the ecological consequences would be negative. Unsuitable as a significant contributor to meeting the growing energy demand of the future.
4. **Biomass,** *renewable*, existing capacity reserves (280 to 450 EJ/yr primary energy). If biomass were to play a significant role (>50%) in meeting the future energy demand, this would lead to an enormous demand for land, in competition with other kinds of land use. Already today, humans use 40% of the total primary production of planet earth to meet their needs (J.Swisher, D. Wilson: Renewable energy potentials, Energy 18 (1993) 437-459. D.O. Hall, F. Rosillo-Calle, R.H. Williams, J. Woods: Biomass for energy – supply prospects, in: Th. Johansson et al.,).
5. **Wind power;** *renewable,* has an enormous potential, in principle. If 4% of the sites suitable for wind farms were actually used, 230 EJ/yr of electricity could be generated.
6. **Photovoltaic;** *renewable*, virtually limitless potential in all regions (estimated between 1,500 and 50,000 EJ/yr of primary energy), but not economical yet at today's energy prices.
7. **Thermal and passive use of solar energy;** *renewable*, virtually limitless potential for energy demand at a low temperature level.
8. **Geothermal,** *conditionally renewable,* immense potential, but of limited use, from the present technical and economic perspective, where the geothermal flux at the surface is naturally strong (volcanoes, geysers).
9. **Ocean energy,** e.g. tidal and wave energy, *renewable.* Niche applications, no foreseeable significant role.

In a certain sense, **ambience heat,** which can be used through heat pumps, also belongs on this list. However, since it can only be used in combination with other energy carriers, it is classed as a method of improving the efficiency of the energy system.

(which is 10% of the present energy use in the EU), an area of 25 million hectare (250,000 km^2) is needed[5]. This is one third of the area of arable land; 22% of the forest area or 12.5% of all the area potentially suitable for biomass production. Of course, there exists a substantial competition with other land uses. Some time ago expectations about setting aside land for energy production were high, but present prospects are uncertain[6].

Table 5.4 Overview of land area in the European Union in 1999 (million hectares). Source: FAO.

Forests and woodland	Permanent crops[7]	Arable land	Other	Total
113	11	75	115	314
36%	4%	24%	37%	100%

Biomass can be applied directly for energy purposes. Direct combustion is still the most common way of using biomass. It may range from small stoves in developing countries, to large industrial boilers, e.g. for the combustion of residues in the pulp and paper industry. In general, large-scale combustion delivers the most efficient and cleanest way of biomass utilization. For the time being it seems to be most interesting to apply co-firing of biomass in existing coal-fired power plants. Up to 20% of the coal in these power plants can be replaced by biomass; modification of the burners is required, but by now this is a proven technology. As in the EU the total coal combustion in power plants is 5.5 EJ (1999), this means that today an increase of biomass utilization does not depend on the introduction of a new conversion technology.

The future technology that is most discussed for biomass utilization is gasification. Under oxygen-limited conditions the biomass is converted to a mixture of gases like methane, hydrogen and carbon monoxide. This gas mixture can be used as energy carrier, e.g. for electricity production in highly efficient combined-cycle power plants. In addition, the gas mixture can be further converted to produce secondary fuels, like hydrogen, methanol or (via Fischer-Tropsch synthesis) synthetic gasoline. These fuels are suitable for automotive transportation.

For wet forms of biomass biological treatment processes are more appropriate. The best-known conversion process is anaerobic digestion. This is a bacterial process in a wet environment in which organic waste is converted to a mixture of methane and car-

5 Assuming average production of 14 dry tons per hectare, a lower heating value of 18 GJ/ton and under consideration of the energy consumption for cultivation, harvest and processing.

6 In the eighties in the European Community expectations about the amount of set-aside land were high. More than 15 million ha of land were expected to be taken out of farming by 2000 if surpluses and subsidies associated with the Common Agricultural Policy would be brought under control. However it turned out that these goals were not met. Reasons are both the restrictions in taking land out of agriculture and the limited demand for energy crops. The obligatory set-aside land for 2001/2002 amounts to about 4 million ha in addition to voluntary set-aside of 1.6 million ha i.e. in total 5.6 million ha. So far no new goals have been set on the amount of land to be set aside.

7 E.g. fruit trees and vines.

bon dioxide. This process is especially suitable for wastewater and manure. Another process, fermentation, can be applied to, e.g., sugar cane and sugar beet to produce alcohol. However, for European conditions, this route to produce liquid fuels is considered less attractive (in terms of chain efficiency and costs) than the gasification-based routes described above. Under development – and considered very promising – is enzymatic hydrolysis that can be used to produce alcohol from wood.

Wind energy

Wind energy utilizes the kinetic energy in flowing air masses. In the eighties, wind turbines with typical capacities of 0.1 MW have been developed and installed. Since then a dramatic increase in unit capacity has taken place, with the biggest wind turbines now having a capacity of 2 MW. Until now most wind turbine capacity in the European Union is on land. By the end of the year 2001, total capacity was about 17,000 MW, with annual growth rates of 30%.

In wind farms it is customary to install between 5 and 10 MW of wind turbine capacity per square kilometer land surface. Various potential estimates have been made and optimism is increasing. Recent understanding is that for the European Union it seems possible to install 250,000 MW of wind turbine capacity on land and 150,000 offshore. The wind turbines would produce about 3 EJ of electricity. The 250,000 MW onshore would, if installed in wind parks, cover about 1% of Western European land, but the land could still be used for certain other purposes.

Solar energy

There are various forms of direct utilization of solar irradiation. Direct use of solar irradiation provides the highest energy production per unit area (see Table 5.5). The first form is heat production through solar collectors. Heat is irradiated on a surface that is thermally isolated from the environment. The heat can be carried away by, e.g., water or air. The most common utilization is for hot water production. Application for space heating becomes possible if the seasonal storage problem is solved. Typical conversion efficiencies from solar irradiation to moderate temperature heat are 30–60%. The total potential in the European Union is less than 1 EJ. An important limitation is the lack of (future) demand for low-temperature heat.

Much less developed, but more promising for the future, is direct conversion of solar energy through photovoltaic cells into electricity[8]. Efficiencies for practical systems reached by now are over 10%; but in the future efficiencies over 20% may be feasible. To date, photovoltaic (PV) power production is still among the most expensive renewable energy sources, but it is also the source that may become the most important in the long term.

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8 Electricity production through so-called 'solar thermal'. In this case, solar irradiation is concentrated; this makes it possible to generate high temperatures, e.g. hot air or steam. This is used to produce electricity. Concentration is only possible for direct irradiation; this limits the application to sunny regions, e.g. the south of Spain.

Table 5.5 Typical specific energy production per unit area from renewable resources.

Renewable energy technology	Energy production (MJ per m^2)	Energy form
Biomass	20–25	crude biomass
	10	electricity
Wind energy[9]	35–70	electricity
Solar collectors	1000–2000	heat
Solar photovoltaic	400	electricity

Table 5.6 Characteristics of global renewable energy use. For comparison: In 1998, total global energy use was about 380,000 PJ/year (380 EJ/year). Note that different energy forms are not fully comparable, e.g. 1 PJ of electricity from biomass replaces more fossil fuel than 1 PJ of heat from biomass. Also the economic value of 1 PJ electricity is higher than 1 PJ of heat. Source: World Energy Assessment.

Technology	Global energy production 1998 (PJ/year)	Increase in installed capacity in past five years (percent per year)	Current energy cost of new systems (¢/kWh)	Potential future energy costs (¢/kWh)
Biomass energy				
Electricity	580	~3	5–15	4–10
Heat	>2500	~3	1–5	1–5
Ethanol	420	~3	3–9	2–4
Wind electricity	65	~30	5–13	3–10
Solar photovoltaic electricity	2	~30	25–125	5–25
Solar thermal electricity	4	~5	12–18	4–10
Low-temperature solar heat	770	~8	3–20	2–10
Hydroelectricity				
Large	9000	~2	2–8	2–8
Small	320	~3	4–10	3–10
Geothermal energy				
Electricity	170	~4	2–10	1–8
Heat	150	~6	0.5–5	0.5–5

[9] In order to produce 6 EJ (which is 10% of present energy use in the European Union) a production area of 25 million hectare is needed[23]. This is one third of the area of arable land, 22% of the forest area or 12.5% of all the area potentially suitable for biomass production.

Overview of renewable energy

An overview of the present use of renewable energy resources is given in Table 5.6. Many technologies are available already, but most of the so-called new renewable energy resources are expensive compared to conventional electricity production, twice as expensive for wind and biomass, and 10 times for photovoltaic solar energy. Technological learning leads to a reduction of costs per unit of energy produced (see figure 5.3), but this is a slow process.

5.4 Imagining the future: possible developments and effects

Taking into account the possible developments on both the demand and the supply side of the energy system, we present four different scenarios for the energy system in the EU in the year 2050: one with constant carbon dioxide emissions after 2010 and three contrasting cases, all of them involving a decrease in the level of carbon dioxide emissions by 75–85% compared to 1990 (and also a reduction in many other pollutants emissions). A business-as-usual type of scenario (indicated with ‘0’) is added for comparison. It represents the continuation of existing trends, like small rates of energy efficiency improvement, gradually increasing final energy demand, an increasing share of natural gas, a phase-out of nuclear energy, and small shares of renewable energy sources. Note that the inclusion of this scenario should not suggest that for a period of fifty years such an image has more than an explorative character. Of course, this remark also applies to the other cases.

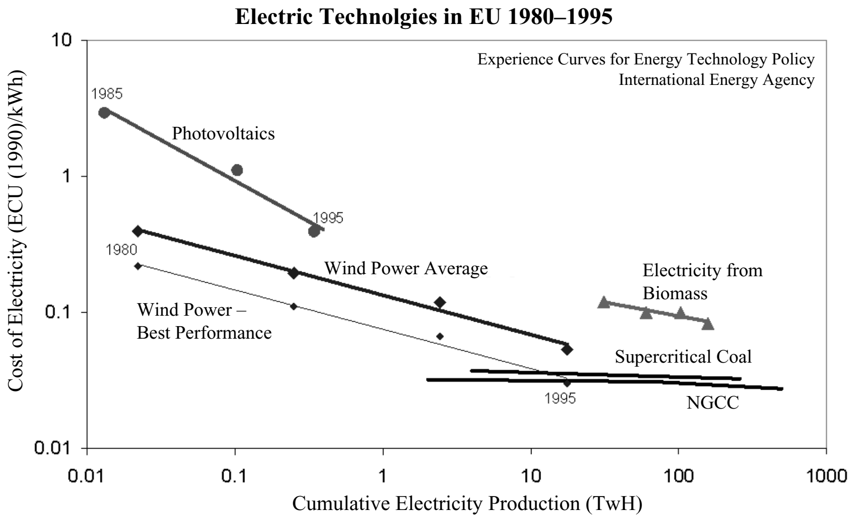


Fig. 5.3 Development of the cumulative electricity production and the unit electricity price of various electricity production technologies. Despite rapid learning rates, especially for photovoltaic, all renewable energy technologies still show higher electricity production costs than fossil-based technologies (supercritical coal fired power plants and NGCC: natural gas-fired combined-cycle power plants).

0. Reference case
I. A scenario with a fairly stable energy demand (however with a shift from heat demand to electricity demand) and a supply system that depends on the cheapest abundant sources available within the carbon dioxide constraint: biomass and natural gas.
II. Same development of demand, but with a smaller dependence on biomass.
III. A scenario with a strong reduction in energy demand.

The input of primary energy by fuel for each of the projections is given in figure 5.4. In scenario I it is assumed that low-temperature heat is supplied mainly by heat pumps and combined cycle district heating plants. Alternatively, a much more decentralized electricity production system is conceivable that is based on small-scale fuel cell generators that supply local heat demands. One third of the biomass production can be based on a variety of waste flows and residues. However, a substantial additional production of energy crops is required. The total land area needed to produce the biomass is 40 million hectares, which is 20% of the present area used for agriculture and forestry in the EU.

This vast amount of land requirement may be considered as problematic[10]. Instead, one may conceive a development that depends on a less space-intensive energy source, like photovoltaic solar energy. Development of this source requires a sustained growth of over 20% per year[11] in the first half of this century and a continuous investment in this energy source. This is presented in scenario II.

Another problem that may occur in scenario II is that the share of intermittent renewable energy resources, like wind energy and photovoltaic solar energy, becomes large. The degree to which intermittent renewables can be integrated into an electricity system strongly depends on the flexibility of the rest of the generating capacity, the availability of storage facilities and the way of power system control. If the non-intermittent generating capacity is sufficiently flexible, it seems possible to allow a share of 30–40% of wind and solar production without storage facilities, and of about 40–50% with sufficient storage facilities (K. Blok, E.A. Alsema, A.J.M. van Wijk, W.C. Turkenburg: The value of storage facilities in a renewable energy system, Proc. of the Sixth EC Photovoltaic Solar Energy Conference, Reidel, Dordrecht, 1985, p. 337–342). Therefore, the even higher share of intermittent renewables in the electricity sector in scenario II requires that part of the generated electricity has to be used for other purposes; a logical use of this energy is the generation of hydrogen through electrolysis for transportation purposes.

Stabilizing final energy demand, as assumed in scenarios I and II, already requires a substantial effort in addition to what may be expected to occur autonomously. Stabilizing energy demand can be considered to be the net effect of annual GDP growth of

[10] Note that alternatively biomass or biomass derived fuels can be imported from other continents. Yet, competition with other land-use claims will occur as well, like those for food, fodder and fibers.

[11] Note that a seemingly small increase of the annual growth rate of photovoltaic solar energy production capacity from 13 to 18% per year leads to a tremendous increase in the contribution of photovoltaic solar energy from 0.6 to 5.5 EJ_e. This illustrates our inability to judge on exponential growth for such long timeframes.

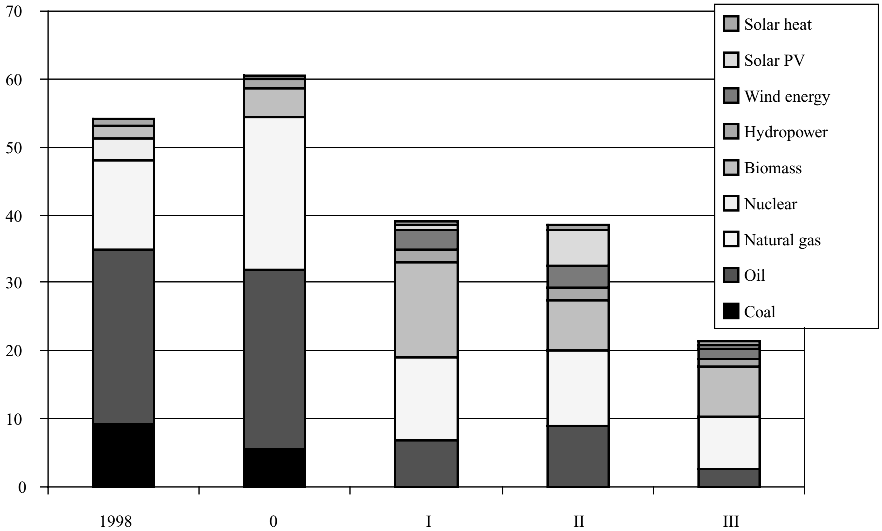


Fig. 5.4 Overview of the primary energy inputs in the year 2050 for the three images[12]. In the case of the wind, solar and hydro, primary energy is defined as the energy content of the electricity and heat produced. In the other cases primary energy is defined as the energy content of the fuel. This gives a suggested underestimation of the value of these renewable energy sources.

2–2½ %, structural effects leading to reduced energy intensity of about ½ % per year and an energy efficiency improvement of 1½–2 % per year (normally it amounts to 1% per year only). Nevertheless, as was shown in section 5.2, a substantial reduction in energy demand seems feasible, if technological progress in energy demand options is high enough. Scenario III shows a reduction of energy demand to about 40% compared to the present level. Compared to the other cases, all renewable inputs, except biomass which is the same as in case II, are reduced.

All three low-carbon images are characterized by a high growth rate of renewable energy, which indicates the transition that is required. In table 5.7, the necessary growth rates are listed. The difficulty of maintaining such growth rates over

[12] The basic data for the year 1998 are taken from IEA/OECD energy statistics. Final heat demand is calculated using present heat production efficiencies of 90% for industry and 80% for the other sectors. Non-energy use of energy carriers is left out of consideration.
For images I and II it is assumed that total final demand is stable until 2050, but the share of electricity in final demand is assumed to rise from 20 to 27%. It is assumed that low-temperature heat demand is for a small part covered through solar heat, but mainly through electric heat pumps (coefficient-of-performance = 6). Industrial heat is covered by combined-generation-of-heat-and-power (electric efficiency 60%; heat efficiency = 30%). Heat not provided from renewable sources or CHP is assumed to be generated from natural gas (electric efficiency 70%). High-temperature industrial process heat is assumed to be produced from natural gas. Biomass is mainly used to produce automotive fuels (biomass-to-fuel conversion efficiency of 90%). The remainder of the fuel use, including those for petrochemical feedstock is from oil products. In image II, part of the fuel is produced from excess electricity through electrolysis (conversion efficiency 90%).

a period of 50 years cannot be ignored. Without any doubt, a continuous effort in invention/innovation and diffusion of new technologies is required to achieve such an ambitious goal. A summary of the different requirements is given in table 5.8.

Table 5.7 Required annual growth rates of the use of various energy sources in the low-carbon images I to III for the period 2000[13]–2050.

Energy source	I	II	III
Hydropower	1%	1%	0%
Biomass	4%	3%	2%
Wind energy	7%	7%	6%
Solar heat	11%	11%	11%
Solar photovoltaic	13%	18%	13%

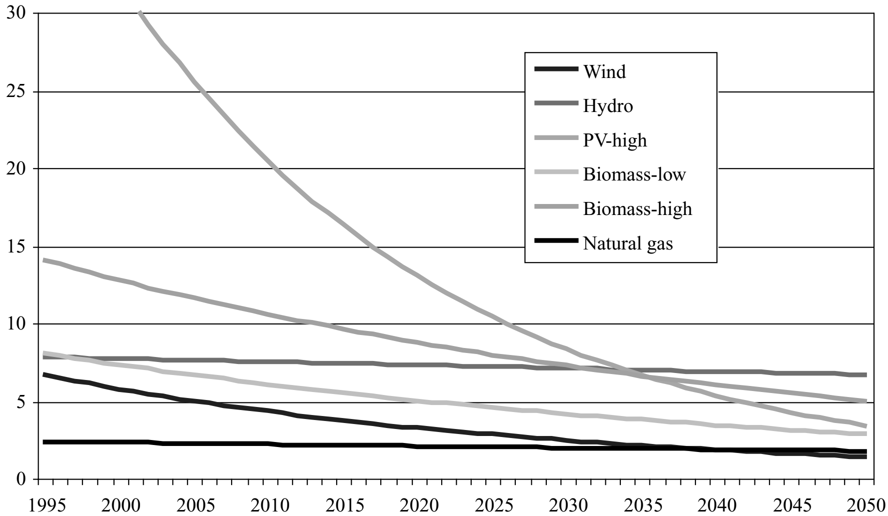


Fig. 5.5 Development over time of electricity production costs for various renewable resources assuming the growth needed for image I (growth rates are taken to be fixed). Costs are in dollar cents per kWh. The following progress rates are assumed (Energy Technology Price Trends and Learning, International Energy Agency, Paris, 1998): wind: 81%; photovoltaic: 82%; biomass: 70%; natural gas combined cycle: 90%. A progress rate of 90% means that costs are reduced by 10% for each doubling of cumulative production capacity.

[13] 1999 or 1998 if more recent data were not available.

Table 5.8 Overview of invention/innovation and diffusion necessary for the transition to a sustainable energy system.

Sector		Invention/innovation	Diffusion
Energy demand sectors	Industry	Development of a number of process innovations (see, e.g. Table 1) Uptake of more inventions to be developed to innovations Development of industrial processes Development of some cross-cutting technologies (high temperature heat pumps, heat exchangers, membranes)	Sufficient rate of implementation of new processes (e.g. through standards) Find methods to bring state-of-the-art technology to energy-extensive sectors Broad introduction of ambitious energy management systems
	Buildings	Development of better building shell components (also for existing buildings) Development of cost-effective heat pumps and fuel cells System approach to development of energy-efficient dwellings Development of energy-efficient electric appliances (best-available-technology approach for broad range of appliances)	Large-scale retrofitting of existing building stock Continuous sharpening of energy efficiency standards for new buildings and new appliance
	Transportation	Development of efficient lightweight cars with hybrid or fuel cell propulsion More focus on other efficient transport systems (efficient trucks, light rail)	Roll-out of new fuel infrastructure
Energy supply	Fossil energy use		Principle of no-heat-without-power to stimulate CHP Adoption of best-available-technology power plants
	Renewable energy	Development of advanced photovoltaic cells and integration in buildings and energy systems Development of advanced biomass conversion equipment (gasification, enzymatic hydrolysis) Development of off-shore wind energy converters Development of high-capacity heat storage systems	Long-term investment (partly non-profitable) in all renewable energy sources to enforce learning Set up a market and regulations for biomass energy feedstocks Arrange physical infrastructure and organization of electricity production in such a way that large-scale integration of small-scale production becomes feasible

Natural gas becomes the most important fossil fuel in all the scenarios presented. Nevertheless, the demand for natural gas (7.5–12 EJ) is somewhat lower than the actual demand in the European Union (13 EJ) and also lower than in a reference scenario. This demand would probably not cause a supply problem. First of all, Western Europe (including Norway) has still substantial reserves. Proven reserves are fairly small (about 200 EJ), but total conventional natural gas resources are estimated to be about 1000 EJ, and unconventional resources 1200 EJ (excluding the vast amount of methane hydrates (H.-H. Rogner: An Assessment of World Hydrocarbon Resources, Annual Review of Energy and Environment, 22(1997)217–262). Western European natural gas resources are 4–5% of world resources (see fig. 4.3). The largest natural gas resources are located in the former Soviet Union and in the Middle East. Increase of the import from Russia via pipelines and from other areas through liquefaction can add to the supply of natural gas to the European Union.

One important aspect is the development of the cost of the various secondary energy carriers. The costs for electricity production are estimated starting from the present production costs and using the idea of technological learning. A well-known rule of thumb is that costs of products decrease with a fixed fraction each time the cumulative production doubles (see chapter 2.3.2). The results depicted in Figure 5.5 demonstrate that learning is a fairly slow process and that it will take several decades before the costs of renewable resources drop to a level which is comparable with the cheapest conventional alternatives.

Finally, in table 5.9 a preliminary analysis is presented of each of the three scenarios with respect to the three aspects of sustainability. Although all scenarios show a strong reduction in greenhouse gas emissions, only scenario III satisfies the 2,000-Watt/cap criterion put forward in chapter 4. The other scenarios correspond to an energy use of about 3,600 Watt per capita, a value which is substantially lower than in a business-as-usual type of development represented by the zero projection.

German readers could ask, at this point, how the Energy Report 2001 of the *Bundesministerium für Wirtschaft und Technologie* must be judged in this context. In that report it is stated that a 40%-reduction of CO_2 emissions by 2020 leads to costs, which adversely affect economic growth.

The focus of the report on efficiency improvements in the buildings and transport area was too narrow. A significantly broader approach – as taken in this study, for instance – is needed to achieve the intended objective. The substantial efforts about regenerative energy technologies in German must be complemented by an equally strong engagement in the area of energy efficiency. Moreover, a much stronger engagement in research and development is necessary for ensuring a continuous development of new technologies. The expenditure in this field, which is low in Germany, at any rate, must grow considerably. This is called for in the present study.

Table 5.9 Preliminary comparison of the four future scenarios with respect to the three sustainability criteria.

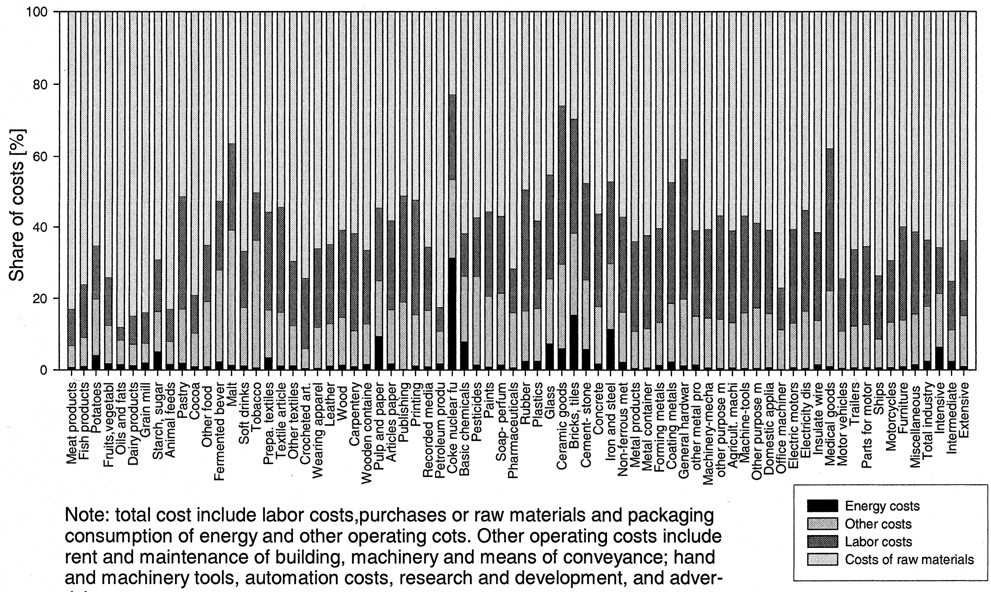
<table>
<tr><th>Scenario</th><th>0</th><th>I</th><th>II</th><th>III</th></tr>
<tr><td>Energy use per capita</td><td>5,500 W</td><td>3,600 W</td><td>3,600 W</td><td>2,000 W</td></tr>
<tr><td rowspan="2">Economic</td><td rowspan="2">Costs of energy system will gradually decrease further. Risks of energy supply distortions.</td><td>Costs probably are somewhat higher than in image 0.
High cost, including high transition costs.</td><td>Low investment image.</td><td>However, high upfront investments in RTD required.</td></tr>
<tr><td colspan="3">Substantial transition costs possible</td></tr>
<tr><td rowspan="2">Social</td><td rowspan="2"></td><td>Effect on European agriculture due to the shift to energy crops.</td><td></td><td>Substantial effort in energy efficiency improvement across all sectors required (probably small effect).</td></tr>
<tr><td colspan="3">Substantial structural changes, with associated employment effects. Total net effect on employment is hard to project, but some sectors, especially the coal and oil industry, will see substantial reductions.</td></tr>
<tr><td rowspan="2">Ecological</td><td rowspan="2">Does not satisfy climate change criteria (carbon dioxide emissions higher than present levels).
Other effects of energy production and use remain (e.g. brown coal mining, air quality effects) whereas others (acid deposition) maybe greatly reduced at a cost.</td><td colspan="3">Most likely satisfy climate change criteria</td></tr>
<tr><td>Substantial land use requirements.</td><td></td><td>This scenario is, probably, most attractive from the environmental viewpoint (reduced energy and material flows).</td></tr>
</table>

5.5
Conclusions: What can be learned from history?

5.5.1
Sustainable energy technologies in the innovation trap

Concerning the question how far the (technical) efficiency potentials of energy supply and application are exploited, and to what extent new (regenerative) energy technologies are introduced in the market, one has to identify the specific conditions and obstacles faced by environmental technologies, which also comprise new energy technologies. Apart from the conditions that promote or hold back innovation, which are discussed in detail in Chapter 2, specific environmental technologies frequently find themselves in an "innovation trap" (more details in Steger, 1998).

First of all, it should be recognized that energy is not an important cost factor in most sectors. There are a few heavy industrial sectors where energy costs may reach up to about ten percent of the total production costs. However, for the vast majority of the industrial sectors, energy costs typically are about 1% of the total production costs or less (see figure 5.6). This is also true for the service and agricultural sector. For households energy expenditures typically amount to a few percent of their total expenditures. This means that for most decision makers, energy is not a very important factor when decisions on investments, purchasing and operational practice are taken. This causes the attention for energy issues as well as the interest for corresponding cost reduction measures to remain moderate.



Note: total cost include labor costs,purchases or raw materials and packaging consumption of energy and other operating cots. Other operating costs include rent and maintenance of building, machinery and means of conveyance; hand and machinery tools, automation costs, research and development, and advertising expenses

Fig. 5.6 The share of energy costs and other cost components in the total costs of enterprises for various sectors in the Dutch economy. Source: data compiled by Andrea Ramirez, Utrecht University.

Secondly, if energy is considered as a cost factor at all, its positive potential in the market is underestimated because the positive external effects of measures (e.g. lower CO_2 emissions) are not, or not fully, taken into account, depending on the situation concerning (statutory) standards. More efficient energy technologies, for instance, often produce monetary cost savings too. But if energy is subsidized (as is the case e.g. in agriculture and in air transport), or if emission limits can also be kept to with technologies, the benefits of environmental sound and resource saving technologies do not take effect in the corporate investment calculation, which distorts the comparison of alternatives in favor of the conventional technologies.

Thirdly, new technologies are at the very "summit" of the learning curve. They are far less mature than the conventional technologies, which in some cases have undergone decades of a continuous improvement process. Small production quantities lead to (initially) high costs compared to conventional alternatives. The "4-stroke combustion engine" used in cars is a good example for the stability of one technology trajectory carried by mass production and continuous improvement. Although this type of propulsion energy involves specific drawbacks in terms of emissions and energy consumption, no potential alternative so far succeeded in touching the dominant position of the combustion engine in transport. It remains to be seen to what extent the fuel cell will bring actual changes beyond a niche existence in emission-limited areas e.g. large cities in California.

Being stuck at the upper end of the learning curve is particularly fatal for regenerative and decentralized energy technologies. As a rule, such technologies are "manufactured technologies", in contrast to the conventional "on-site-technologies" (e.g. power plants or refineries, which are erected in one site as a unique installation). Hence, the rapid realization of economics of scale is of strategic importance for the competitiveness of manufactured technologies against on-site technologies.

The fourth point is that energy technologies are rarely used as "stand-alone" systems. They are often embedded in grids or power lines. They must maintain compatibility within the chain by keeping to narrowly defined standards (e.g. petrol engines), or they are tailored to very specific applications as chosen by the buyers. Dedicated services and training centers have developed around the conventional technologies and their infrastructures. Such essential support structures are largely absent in the field of more efficient or regenerative energy technologies. Furthermore, the products of new technologies often do not fit into standards and complementary infrastructures, which have to be built up from scratch then

Fifth, the problem of "sunk cost" is particularly acute in the capital-intensive energy sector. Once a facility (e.g. a power plant or a refinery) has been erected, the capital raised for it has "sunk". Compared to early decommissioning (which entails high social and dismantling costs), any (continued) operation that still provides some collateral beyond the variable costs is economically rational. For the energy sector this means that new technologies have to compete with facilities that have been written off already (for instance nuclear power plants older than about 17 years, with a remaining service life of up to 35 years), or with installations that do not need full cost coverage. – The phenomenon of sunk costs also explains why unprofitable facilities are maintained for long periods in capital-intensive industries. – On the other hand, new investors may be deterred by the risk of getting involved in a price war.

Consequently, opportunities for new energy technologies lie in slowly growing markets, in the time window, which may be very narrow, when new investments are decided on, at the end of the economic lifespan of old facilities.

5.5.2 Substitution of energy carriers

The substitution of energy carriers is nothing new in the history of industrial development. While coal, as the energy carrier of the industrial revolution, first broke the limits of the previously dominant, regenerative energy carries and then replaced them, coal itself was increasingly replaced by oil since the beginning of the 20th century. This development did not occur at the same pace everywhere: In the US, where there were relatively few large coal mining regions, compared to Europe, and where the industrial structure of the, then, coal-based "tar chemistry" was not yet established to the same extent, oil could more easily conquer market shares as early as in the late 19-hundreds. In Europe, it was more difficult for oil to compete with coal. Only Churchill's strategic (i.e. not economic) decision to switch the British Royal Navy to oil in order to increase the range and speed of the vessels, and then the Great War brought the breakthrough of oil to secure market segments, most notably in the transport fuel sector. However, in regions where oil had to compete directly against coal, the substitution process, e.g. in navigation, stretched over decades. Before the Great War, there were only 500 oil-powered trade vessels. With the development of the Diesel engine and more effective oil-fueled boilers, the share increased to 54% by 1939 (24% for Diesel engines). After the World War II, which brought another push towards oil, this trend accelerated further: In 1957, only 8% of all trade vessels were powered by coal; by 1970 this share had shrunk to virtually zero.

The advantages of oil over coal in powering ships (and other transport systems) were obvious:

– Longer range with less bunker space (i.e. more freight space);
– Improved safety and easier operation with fewer staff;
– Quicker refueling.

The more the oil industry grew into a (or the first) global industry with falling production and transport costs, the more competitive became the price of oil. Today European coal can only be used (and can preserve market shares for the cheaper imported coal) in connection with state measures (electricity generation from coal, for instance, in Germany) or in specific technological applications (e.g. steel production).

However, after the oil price crisis of 1973/74, oil itself became the subject of substitution processes, especially substitution by natural gas in the areas of industrial and residential heating, and by nuclear energy in the electricity generation sector, where heavy oil power plants disappeared in many countries.

Considering the various substitutions of energy carriers, one can identify a number of common factors that were necessary for effecting a successful substitution:

– The new energy carrier must offer additional benefits beyond its economic advantages (e.g. oil is cleaner and easier to use than coal).

- Hardly any substitution was untouched by policy. Some political interventions were in favor of the new energy carrier, others favored the old carrier (often in the sequence: first support for the new energy carrier, then protection of the old ones, if the new competition turned out to be too successful).
- Once the new energy carrier has crossed the threshold of a “critical mass”, its diffusion develops faster in its favor.
- The economic lifespan of the energy infrastructure that complements the fuel determines the speed of diffusion. (Large differences in the fuel costs or lower changeover costs can, of course, change the economic lifespan of facilities.)

These factors will also dominate the substitution of fossil energy carries by regenerative sources.

5.5.3 Final conclusions

The discussion so far has shown that energy efficiency innovations have a considerable potential to reduce, significantly, CO_2 emissions without giving rise to concerns about grave economic costs or structural ruptures. The reduction potential of these innovations is difficult to quantify for the long term, since we know little about the speed of the diffusion process by which the energy efficiency innovations will penetrate the market. This diffusion speed is not “given”; it rather depends on the actors, including state policy. As an important point for the recommendations for action, one must state, firstly, that accelerating the diffusion of energy efficiency can be an important lever for shaping a more sustainable energy system.

Secondly, it is clear now that the present targets for regenerative energy sources (e.g. generating 12% of electricity in Europe from regenerative sources by 2010) will not be met if they are not promoted massively in the future. (We will see that the “how” of this promotion is by no means a trivial question, even if the “whether” has been answered convincingly.) This applies, especially, to the long-term transition to a solar-based energy system.

Thirdly, the relationship between energy efficiency and regenerative energy sources has become clear: Even under optimistic assumptions concerning the development of regenerative energy sources, it is impossible to provide sufficient contributions to energy supplies, if the growth of energy consumption in the developed countries continues. Only if the energy efficiency potentials are exploited, i.e. if energy consumption is reduced, the regenerative sources can reach a share of ca. 50% in 2050.

As a fourth point, explorative considerations concerning earlier subsidies for energy carriers do suggest that the substitution is seen to develop faster once a “critical mass” has been achieved.

Again, the analysis of the “innovation trap” clearly shows that the innovation potentials of energy efficiency and regenerative sources will materialize quasi “automatically” or as a trend. Hence, there is an obvious need for action, which is not met to any sufficient extent, however, as the following analysis will show. We will examine the reasons for this before we develop our recommendations for action.