ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

# ENERGY

# The Next Fifty Years

# Energy:
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Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

– to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
– to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
– to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

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# Foreword

In the coming decades, the energy sector will face an increasingly complex array of interlocking challenges – economic, geopolitical, technological, environmental – and not just in the OECD countries. As the developing world's population continues to expand, the energy needs of billions of additional people in rural and especially urban areas will have to be met. Meanwhile, supplies of conventional oil and conventional natural gas are expected to decline in the not-too-distant future, becoming increasingly concentrated in the Middle East (oil) and in such countries as Russia and Iran (gas). A further constraint on the use of conventional energy resources, including coal, will almost certainly come into play as increasingly tight limits are placed on the total amount of greenhouse gases that can be released into the atmosphere – and that constraint will in turn lead to greater interest in alternative energy sources and technologies. The responses to this varied range of developments will play a crucial role in shaping trade and investment flows, competitive positions, and the structure of economies across the globe, while simultaneously determining mankind's capacity to construct a sustainable future.

Meeting these challenges will require very long lead times. Indeed, renewing the existing patterns of energy production and consumption – transport and other technical infrastructures, the layout of cities, the nature of the industrial capital stock, current technologies, values and attitudes, etc. – could take as long as fifty years.

To examine these issues, an OECD Forum for the Future conference was held in co-operation with the International Energy Agency (IEA) in July 1998, in Paris. The event brought together leading players from government, business and research, to explore the challenges and likely trends and developments in world energy through 2050; to examine the opportunities and constraints posed by the likely evolution of key factors such as the geopolitical landscape, new modes of transport and energy technologies, and climate conditions; and to consider, from a multidisciplinary perspective, the range of possible strategic responses.

The conference was organised into four sessions. The first aimed at providing an overview of the energy outlook – first to 2020, then to 2050 – with a view to identifying some of the key uncertainties and challenges. The geopolitical dimension and environmental issues formed the focus of the second session, while the third assessed the likely evolution of energy demand patterns and the potential for energy technologies, old and new. The fourth session was devoted to discussion of strategic options for policy-makers and corporate decision-makers.

This publication brings together the papers presented at the meeting, as well as an introduction to the main issues prepared by the Secretariat. The book is published on the responsibility of the Secretary-General of the OECD.

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# The Long-term Future for Energy: An Assessment of Key Trends and Challenges

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Although the uncertainties are considerable, there is a fair degree of consensus on the energy outlook for the next twenty years; possibly the main reason is that long-term energy trends are not expected to be subject to radical changes over this time scale. Capital turnover is low, and in power generation, housing and to a lesser extent transportation, most of the capital stock of the coming twenty years will use current (or past) technologies. Moreover, the dynamics of energy demand have been quite stable since 1982, and are generally expected to continue along their long-term trajectory. Around 2010/2020, however, the picture might well begin to change. New technologies will probably come on stream, new generations of capital stock and infrastructure could emerge, and on the energy resource side, conventional oil production is expected to decline while new energy sources, especially non-conventional oil and renewables, move increasingly to the forefront.

## 1. The next twenty years: business as usual?

The IEA's "business as usual" scenario, presented in the next chapter by Jean-Marie Bourdaire, is based on fairly standard economic and demographic assumptions. World economic growth is projected at 3.1 per cent per annum, close to its average for the past twenty-five years, with higher growth rates in developing countries and the transition economies, and lower rates in the OECD area. World population is expected to increase substantially, albeit at a gradually slower pace, reaching 8 billion in 2020. Total energy use rises by 2 per cent per annum and energy intensity decreases by 1.1 per cent per annum. There is a risk, however, that energy efficiency improves more slowly than expected in China and the transition economies. $CO_2$ emissions would rise in parallel with primary demand – in other words, slightly faster than in the past – due to the levelling off of nuclear power generation and to rapid growth in coal use in China and other Asian countries.

One striking feature of the overall picture is the existence of an autonomous energy efficiency increase, resulting from the introduction of improved technologies (driven by the search for competitive advantages) and evolving hand in hand with GDP growth. This suggests two contrasting possibilities for the future. On the one hand, if prices and institutional conditions remain unchanged, it could prove difficult to move away from this autonomous trend. On the other hand, if prices and/or behaviours change, *e.g.* because of the introduction of new taxes or regulatory reforms, then there is a real potential for vast improvements in energy efficiency. These could amount to 20 or 30 per cent in 2020, according to the second assessment report of the Intergovernmental Panel on Climate Change.

***Relative stability in energy demand patterns***

Three uses are considered in energy demand: electricity, mobility, and stationary uses (mostly heating). In the OECD countries, electricity and mobility have been remarkably stable in the past, growing broadly in line with GDP in spite of the oil price shocks of 1973 and 1979. Stationary uses, on the other hand, have been affected by the oil shocks through sharp energy efficiency increases (mostly due to price signals, and partly to policies), rising demand for low-energy service activities, and the relocation of some industrial activities to developing countries.

These trends are largely expected to continue in the coming decades, but with some important variations. In developing countries, energy use is likely to rise markedly, due to higher living standards, population growth, rapid urbanisation and the gradual substitution of noncommercial fuels by commercial fuels. The outlook is less certain in the transition economies, where past observations on energy intensity cannot be used to foresee the future. OECD countries, finally, might experience some saturation in stationary uses – heating in particular – but the extent and timing are difficult to predict. In short, non-OECD countries will play a much more important role than they do at present, both in terms of demand and supply, and in terms of $CO_2$ emissions.

***Fossil fuels remain predominant in the energy mix***

Up to around 2020, energy use will continue to be largely dominated by fossil fuels. Oil consumption will be driven mainly by transport needs, and by the fact that oil will remain the “swing” energy, *i.e.* that which fills the gap when other energies are not available to a sufficient extent. Use of gas – where it is available – will grow rapidly as the preferred fuel for heating, process use and power generation; coal use will grow, albeit more slowly in the power generation sector, where gas is not available or is more costly than coal. The major non-fossil sources (nuclear fission, hydropower, biomass) will probably see their shares in overall supply decline. Biomass use in particular, still predominant in some developing countries, could be reduced by a shift from noncommercial to commercial fuels as real incomes increase in those countries. Oil and gas prices look set to remain fairly stable up to 2010, but then increase in real terms by some 50 per cent at some date between 2010 and 2020, as marginal supply shifts from conventional to non-conventional oil. However, with supplies of conventional oil increasingly concentrated in the Middle East, and with reserves of natural gas in Russia, Iran and parts of Central Asia becoming more important, the probability of short-term price disruptions and oil shocks could well rise.

The electricity outlook also is dominated by the use of fossil fuels, at least if the least-cost criterion is applied in forecasting choices of new generating plants. Nuclear, hydro and other renewable sources are not universally competitive under currently expected price structures and/or suffer from a variety of difficulties in gaining public acceptance, so that any significant expansion will have to come from deliberate public policy decisions. In Europe, North America, Russia and the New Independent States, excess of generating capacity over peak demand will need to be resorbed. Coal use is expected to remain heavy in North America as well as in China and other developing countries. Gas use should develop rapidly, in particular in producing countries, partly in combined-cycle generating plants. Oil, finally, will continue to be used as standby fuel in times of peak demand, gas supply disruption or gas price increases. All in all, at the 2020 horizon, conversion rates are expected to improve slightly thanks to (admittedly low) capital turnover. Electricity capacity will have risen by 3 500 GW (gigawatts), half of which would come from China and other developing countries, and a third from the OECD area.

## 2. Beyond 2020

In many respects, 2010/2020 could prove to be a watershed in the transition of energy systems. A variety of forces are at work. The world population will have increased by more than 2 billion people by 2050, the vast majority living in cities in the developing world. Moreover, the OECD countries will be an increasingly smaller energy player in the world in terms of demand, production and trade, but nonetheless remain important as a supplier of technology. More countries will share concerns about the security of energy supply that hitherto preoccupied primarily OECD countries.

While the energy mix picture is unlikely to present any major disruptions compared with today, major changes could occur in the oil and gas supply, and climate change policies may have a large impact. Trade could well increase as local production of oil and gas peaks in some parts of the world, notably in most of the

OECD producing countries. New technologies are set to emerge and new infrastructures will be built to sustain production and facilitate trade, particularly in the gas sector. In many countries, public energy industries are likely be privatised, leading to more competition in energy networks. One of the major drivers of these changes will probably be the shift of demand from raw products (biomass, oil) to more convenient energy services.

This transition of the world's energy sector could well accelerate over the period 2020-2050. The kind of energy systems that will emerge will be shaped by a multitude of opportunities and constraints. For example, many end-use devices, such as cars, industrial processes, heating systems, parts of the building stock and infrastructures will begin to be replaced by new technologies, and many existing power plants will be at the end of their lifetime. By 2050 all energy technologies and devices will have been replaced at least once, offering a wealth of possibilities to set the evolution of both the economy and society on a much more energy-efficient path. However, technologies – new and old – take time to produce and diffuse, and there is currently concern that expenditures on energy R&D are on the decline. Moreover, increases in concentration of greenhouse gases in the atmosphere over the longer term will make it essential to invest in technologies and policies that allow compliance with stricter environmental targets. And oil production will probably have started to decrease, followed closely by gas; even if non-conventional oil and gas resources fill the gap for some time, substitute fuels will eventually need to be found.

### *Four scenarios*

As the chapter by Arnulf Grübler reports, the International Institute for Applied Systems Analysis (IIASA) has developed four scenarios – incorporating technologies, resources, infrastructures and financial institutions – to describe approaches to alternative energy systems over the very long term. In order to widen the field of possibilities, any technology that is operational as of today has been integrated in the analysis, irrespective of its potential commercial viability. Technologies that are not yet operational, such as nuclear fusion, have been excluded as they are not expected to play a significant role in the next half-century.

In Case A, which contains two scenarios, free trade, favourable geopolitics and rapid economic restructuring sustain world economic growth, which attains an average of 2.7 per cent per annum between 1990 and 2050. In turn, high growth enables faster turnover of stocks and facilitates structural change in the energy sector. Efficiency improvement is moderate (1 per cent per annum). Scenario A1 sees a more intensive tapping of oil and gas resources, both conventional and unconventional, thanks to technological change, and a late transition to acceptable nuclear and new renewables. Carbon emissions reach 12 Gt (gigatons) by 2050 and

15 Gt by 2100 (7 Gt in 1995). In Scenario A2, conventional oil and (especially) gas are managed efficiently as transition-fuels to a post-fossil era where nuclear and renewables (principally biomass and solar) dominate. Carbon emissions therefore gradually stabilize (9 Gt in 2050) and decrease (7 Gt in 2100).

Case B is a middle course scenario, characterised by incremental change in technology, trade liberalisation, and take-off in Southern countries. World growth averages 2.1 per cent per annum, and energy efficiency improves by only 0.8 per cent per year. Reliance on fossil fuels is high and lasting, implying in particular a stabilization of the share of coal in primary energy. Carbon emissions first grow moderately (10 Gt in 2050), then accelerate (14 Gt in 2100). Major tensions emerge after 2020, with fossil fuel resource depletion, the financial burden of developing new energy sources, and the consequences of considerable environmental damage.

In Case C, finally, technology diffusion and international relations are mobilised in favour of ecological goals and international redistribution. The international trade regime integrates environmental standards and sustainable development objectives. Carbon taxes somewhat reduce growth in the OECD area, but are recycled (and therefore sustain growth) in developing countries. All in all, the annual GDP growth rate averages 2.2 per cent between 1990 and 2050. Small-scale renewable energy sources help to slow the urbanisation process. Nuclear energy gains momentum with the emergence of a new generation of safer reactors. Energy efficiency improves by 1.4 per cent per year, and economic growth and energy demand are significantly de-linked. Carbon emissions decrease to 6 Gt in 2050 and 3 Gt in 2100.

An important aspect of these scenarios is their treatment of the long-term impact of environmental policies on growth. This issue is traditionally analysed using macroeconomic models in which the costs of environmental damage are not taken into account, and the dynamics of economic growth are poorly reflected. Consequently, environmental policies aimed at curbing greenhouse gas emissions systematically result in a loss of welfare and in lower economic growth in these models. The longer-term scenarios of IIASA, in contrast, describe a world in which appropriate policies not only can preserve the environment, but also help cleaner and more efficient technologies to emerge, and eventually sustain economic growth.

*Common features of the four scenarios*

Some features of future energy systems seem to be common to all scenarios. The first of these is the assumption that there is no natural constraint on the potential supply of energy for the next half-century, and even beyond. If potentially recoverable quantities are included, coal, oil, gas and uranium resource bases are enormous. Alone the solar energy transmitted to the earth every year is close to 130 000 Gtoe (gigaton oil equivalent), which compares to a current total energy consumption of 9 Gtoe. The constraints are not on the potential itself, but on how it will be exploited. They are mainly technical, economic, environmental and political.

The second common feature of the scenarios is that, although the peak of the fossil era will probably have passed, oil and gas will still provide huge quantities of energy through 2050, and decline more or less rapidly afterwards. Renewables (including biomass) emerge in all scenarios as the major source of energy in the longer term, albeit at substantially different levels. The future of nuclear fission, by contrast, will depend upon improved technology and commercial viability as well as public acceptability, taking into account both the safety and the security dimensions.

The general patterns of final energy use are also converging among scenarios. The contribution of electricity increases in all cases. Hydrogen use is expected to develop as well as methanol – but only once it has become more competitive and a hydrogen infrastructure is built. Consumers will push for more flexible, convenient, clean energy services, accelerating the shift from resource use in its original form (biomass, coal) to systems of energy conversion and delivery.

As a consequence of this shift, investment needs are expected to level off (at around 3-4 per cent of gross world product) in energy supply and to rise sharply in end-use activities. Attracting savings to finance supply-side investments might prove more challenging than in the past, when large flows of public funds were oriented towards mainly state-owned energy firms. It could necessitate in particular the removal of institutional barriers, reform of pricing policies, and higher rates of return on investments. A major advantage of high supply-side investments, however, is their potential capacity to contribute to increased energy efficiency beyond the autonomous trends.

*Uncertainties*

The long-term picture that emerges from these IEA and IIASA projections contains a number of significant uncertainties. These are in particular related to two major issues: energy security and the geopolitical outlook on the one hand, and environmental impacts and policies on the other. Important difficulties might surround key aspects of demand projections – such as potential saturation levels in OECD countries (*e.g.* in heating and household appliances), future patterns of mobility (especially transport) in both OECD and non-OECD countries, and the question of increasing energy efficiency over and above past achievements.

Finally, there are also important question marks over the potential impact of new technologies (in the field of energy production and energy systems more generally).

Other uncertainties surround key assumptions of the scenarios. The first questions relate to productivity growth and, ultimately, economic growth in the very long term. In particular, there are divergencies of view on the likely composition of economic growth in non-OECD countries over the coming decades. At the very least it seems safe to assume that, even though developing countries will not bypass steel, machinery, chemical and other industries, the changing nature of production and user technologies (especially the pervasiveness of microelectronics) will ensure they do not repeat exactly the industrialisation pattern of OECD countries. There are, however, regional models which suggest that "leap-frogging" in the catch-up process between some developing and developed countries could prove faster than foreseen, with the former shifting rapidly to light industry and service activities. In either case, energy intensity in those countries could decline faster than expected. Moreover, as regards the transition economies, there are significant doubts surrounding the extent, length and consequences of industry restructuring.

A second set of uncertainties pertains to the demographic dimension. Population development can be estimated over a twenty-year period with some degree of confidence. Furthermore, the very fact that annual increases of population peaked in 1990 and are now in slow decline allows much better extrapolations than the ones made previously. World population could peak before 2050 at 8 or 8.5 billion. Nevertheless, the potential cumulative margin of error over a period of fifty years is more worrisome.

A third set of uncertainties concerns oil reserves. Some experts argue that given the existence of diminishing returns in oil prospecting, and the strong possibility that estimated ultimately recoverable oil reserves (EUR) are lower than generally believed, production could start to dwindle sooner than expected – according to some estimates (EUR of 1 800 billion barrels), as early as 2007. This finding appears to be fairly robust: even if recoverable oil stocks were at 2 600 billion barrels, the mid-depletion point would only be postponed by eleven years, to around 2018-19.

## 3. The geopolitical landscape of the next decades

One of the most difficult and highly speculative exercises in the assessment of future energy trends is imagining the geopolitical context in which they are likely to unfold. However, an evaluation of recoverable reserves of conventional fossil fuels and their geographic location provides a useful first line of inquiry.

### *Growing regional concentration of oil and gas*

One of the major conclusions of long-term energy projections is that fossil fuels will still dominate the energy outlook for at least thirty to forty years. Ultimately recoverable reserves of conventional oil are estimated to be in the range of 2 to 3 trillion barrels, taking into consideration technological advances in exploration and exploitation. Based on regional reserve estimations, world production of conventional oil is expected to peak at some date between 2010 and 2020. According to the IEA, the growing gap between supply and demand would lead to a price rise from $17 to $25 per barrel (1990 dollars), and would be filled by non-conventional oil. Development of non-conventional supplies, however, necessitates large investments; moreover, as its availability might be less secure than that of conventional oil, it might provoke temporary mismatches between global supply and demand.

With reserves estimated at 1.9 trillion oil equivalent barrels, natural gas production is not expected to peak before 2020. Prices, however, will probably move along with oil prices, as the two products are highly interchangeable. OECD Europe and Pacific regions are expected to rely increasingly on imports: from Russia and North Africa by pipeline to Europe, in the form of liquefied natural gas to Japan and Asia. Gas prices in North America might rise as gas reserves there come under pressure from high levels of production. As in the case of oil, considerable amounts of capital will need to be mobilised in order to develop gas production facilities and related infrastructure.

The extrapolation of global oil demand and non-Middle East supplies shows a widening gap soon after 2000 which is expected to be filled by rising production in the Persian Gulf and the Arabic peninsula. According to the conventional view, South East Asia and Japan, and to a lesser extent Europe and the United States, will increasingly rely on oil supplies from that region, at least until non-conventional oil enters the market in big volumes. Such concentration might be a matter of concern in terms of energy supply security. Admittedly, the OPEC's most likely strategy will be to rely on rising volumes as demand increases and other producers fall out of the race, and to maintain low prices in order not to encourage demand shifts and new entries. Political uncertainties in the region, however, have become larger than ever: the political stability of all the major oil-producing countries seems fragile; the Israeli-Arab peace process has virtually stopped; the case of Iraq remains unsolved. The same kind of difficulties arise for gas, which is expected to become a crucial element of energy supplies after 2020, while major gasfields are concentrated in Russia and Iran.

### *Growing interdependence*

Recently discovered Central Asian oil- and gasfields, the size of which could be in the same order of magnitude as those of the North Sea or even bigger, certainly change to some extent those geopolitical conditions. But whether they ease the security of supply risk remains an open question. They also illustrate another essential aspect of future geopolitical conditions, namely the growing interdependence between producers and consumers and the need for increased co-operation among companies, among countries, and between the private and the public sectors. To begin with, exploitation of the region's resources is only at an early stage and huge investments are needed, mainly based on foreign capital and technology. Major improvement in local political conditions and in the extremely uncertain legal and economic environment seems to be a prerequisite to the full exploitation of the region's potential. Moreover, whatever the choice of the region's major oil and gas outlets (Europe by pipelines, via Armenia and Turkey, via Russia, or via Iran; Asia by sea, via Afghanistan and the Indian Ocean), long-term co-operation between the countries of the region will be needed.

### *Changing patterns of trade and investment in energy products*

In the longer term, however, the geopolitical deal could be substantially modified by qualitative changes in energy supply and demand. Long-term energy scenarios, based on a variety of primary energy mixes, show a remarkable convergence among countries of end-use patterns, driven by consumers' preference for more convenient, flexible and clean energy forms. As a consequence, patterns of energy trade are expected in all cases to shift from primary to secondary energy. Exporting countries will have an incentive to increase their revenues by transforming primary sources into value-added exports. As secondary fuels can often be produced from a number of different primary sources, trade flexibility might increase, reducing geopolitical concerns.

Finally, although fossil fuels are expected to remain predominant for some decades ahead, the development of alternative sources of energy, in particular renewables and nuclear energy, could ultimately change the landscape. Renewable resources would probably be much more evenly distributed among countries than is the case for fossil fuels. Production might be largely decentralised, and regional trade might develop at the expense of global trade. Nuclear fission, on the other hand, may have limited prospects in OECD countries, but could well develop rapidly in non-OECD countries, notably in Asia. This could in turn significantly reduce the dependency of China and other Asian countries upon Middle Eastern fossil fuel supplies. At the same time, however, a surge of nuclear power programmes in Asia could act as a springboard for the broader-based revival of the nuclear industry (electricity generation, processing of nuclear fuels, waste disposal, etc.), with important implications for future flows of trade and investment in the nuclear sector.

## 4. The environmental dimension

The current global energy system, predominantly based on fossil fuels, is inherently linked to the increase of atmospheric $CO_2$ concentrations and thus to accelerating perturbation of the global climate system. The average per capita consumption of energy varies by more than a factor of 20 between industrialised and developing countries, with the risk of a fourfold increase in energy demand in the developing countries as industrialisation and urbanisation take hold and accelerate further. High energy use in industrialised countries is driving increases in global energy use through the worldwide diffusion of lifestyles and technologies. As Dieter Imboden and Carlo Jaeger point out in their chapter, gradual, marginal changes, though important, will be insufficient to reach an environmentally sustainable energy system within the next fifty years, suggesting that the present energy system is not sustainable and that a de-coupling of energy utilisation from economic growth is required for a transition to one that is.

### *Rising levels of risk and complexity*

The extent of and risks attached to the various kinds of pollution – conventional and toxic air pollution, the greenhouse effect, radioactivity of nuclear wastes, production site accidents (nuclear, gas, hydrocarbons), transport accidents (tankers, pipelines), landscape damage, etc. – need to be carefully assessed, as too much focus on one could have multiplying effects on the others. Moreover, one might face in some cases a trade-off between two types of pollution. Direct injection engines, for instance, could substantially reduce $CO_2$ emissions of cars by 2010, but at the expense of higher $NO_X$ emissions, thus substituting to a certain extent local pollution for global pollution.

Looking to the decades ahead, it is generally recognised that technologies allowing a reduction of local pollution to acceptable levels are within reach, as long as enough attention is given to research and development and technology diffusion in these sectors. The technologies will not, however, necessarily address the problems of global climate change and greenhouse gas emissions.

### *The challenge of climate change*

Perhaps the most challenging environmental issue for the international community for the coming decades will be global warming. In recent years, and especially since the Rio Summit in 1992, many countries have taken new initiatives to address climate change. At the international level, the United Nations Framework convention on Climate Change entered into force in 1994 and commits parties broadly to the common objective of stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (manmade) interference with the climate system. The convention commits both developing and developed countries to take climate change into account in their social, economic and environmental policy frameworks; to co-operate in scientific, technical and educational matters; and to share information. It also commits parties to promote technology transfer and sustainable resource management. Following the principle of "common but differentiated responsibilities", the convention also commits developed countries to take specific action to mitigate greenhouse gas emissions.

In December 1997, agreement emerged on the Kyoto Protocol which strengthens developed country mitigation commitments. The Protocol commits developed countries to reduce their overall greenhouse gas emissions by at least 5 per cent in the years 2008 to 2012 compared to 1990 levels and sets out differentiated targets for individual countries. Emission reduction targets are comprehensive, covering six types of greenhouse gas and hence activities from a wide variety of socio-economic sources and sinks (*e.g.* energy supply and use; industry; agriculture; land use change and forestry; and waste). Energy-consuming activities are nevertheless responsible for the majority of greenhouse gas emissions in developed countries, and will therefore play an important role in countries' implementation strategies. The Protocol also establishes a number of market mechanisms that are intended to allow parties to work together to achieve reduction targets at least cost. These include joint implementation, emission-trading, and the clean development mechanism. The latter foresees project-based transactions between developed and developing countries to further sustainable development and to generate emission offsets for investors from developed countries.

The precise modalities remain to be decided; these will determine the overall costs and effectiveness of the agreement. Participating countries disagree on a number of important issues, including timing and rules for the use of market mechanisms, and the balance between investment in mitigation through international market mechanisms and that through domestic action. Despite such difficulties, the Kyoto Protocol is widely perceived as a watershed in the international management of global environmental issues. There is wide recognition of the need to continue strengthening international co-operation to address the threat of climate change.

In a long-term perspective, the need to limit atmospheric concentrations of greenhouse gases to a certain level in order to avoid too dramatic a change in climate – say, to 450 or 550 ppm $CO_2$ equivalent – points to an upper limit for cumulative emissions between now and the future target period. Such a target implies a radical drop in greenhouse gas emissions, and a break in present energy-economic trends. This gives rise to the problem of finding an optimal time path, new modes of international co-operation, and innovative policy incentives to achieve such targets in a cost-effective way. A key will be to move towards non-fossil energy systems and to encourage consumers and producers to take environmental concerns into account in day-to-day decisions. Government policies will have an important role to play in ensuring that producers and consumers are provided with clear market signals and with incentives to make the transition to a future with low greenhouse gas emissions.

***The trade-off between emissions control and economic growth – fact or fiction?***

One of the main issues of climate policy will be the cost, either real or perceived, of reducing pollution. Obviously, abatement should at first be obtained by so-called "no-regret" measures, which have environmental benefits at no or very little economic cost, and actually may even have economic benefits. Such measures might range, *inter alia,* from eliminating subsidies that enhance greenhouse gas emissions to "green" labelling and improving consumer information on energy use in businesses and organisations. However, some of these steps are politically difficult to enact (*e.g.* removal of subsidies), and it is unlikely that the resulting improvements will suffice to control global emissions. As environmental externalities are hardly incorporated in economic growth measures, it is generally assumed that more far-reaching policies – using economic tools such as carbon taxes, tradable permits, or regulation – will generate increasing costs. According to this point of view, therefore, there is a trade-off between greenhouse gas abatement and economic growth (or at least – from a corporate or national point of view – competitiveness).

Several arguments, however, relativise and may even refute the existence of such a trade-off when climate policies accompany a shift to sustainable consumption and production through technical change. First, the global warming is itself likely to eventually have an economic cost which would be reduced if emissions are curbed. Second, innovation and technological breakthroughs can create new business opportunities, notably by enhancing energy efficiency. Backed by adequate education and training, technical change could create more jobs and/or enhance productivity, therefore improving the efficiency of economies. Third, the process of change could yield increasing returns, notably linked to learning-by-doing, so that beyond a certain point the costs of change decrease.

All in all, while incremental change seems to come up rapidly against a cost barrier, large-scale change might well reconcile greenhouse gas abatement and economic growth.

## 5. Future developments in energy consumption and end-use technologies

Of the three major uses analysed in primary energy demand, namely electricity, transport, and stationary uses, the first two have in the past tended to expand in OECD countries broadly in parallel with GDP. Stationary uses, on the other hand, have declined as a share of GDP due to the move towards electricity, the achievement of substantial efficiency gains, and the general shift within economies from industrial to service activities. Another factor has been the quick decline of biomass (used as a noncommercial fuel prior to the two oil shocks). This has gone together with the end of the process of transfer from the corresponding uses towards commercial heat, which has yet to occur in most developing countries. In business-as-usual projections of energy demand, these trends are usually prolonged for the next decades in OECD countries, while developing countries are expected to experience a relative catch-up in per capita energy consumption. Ultimately, however, a whole host of factors, ranging from socio-demographic evolutions and new end-use technologies to the globalisation of economic activity and the emergence of the information society, are expected to have an important bearing on energy needs.

### *The impact of ageing populations and rising incomes*

One of the key demographic evolutions of the coming decades, common to all OECD countries as well as some major developing countries, is ageing. But its impact on energy consumption is likely to be ambivalent. Population numbers will gradually level off, but household numbers are expected to grow fairly fast due to the reduction in household sizes. Single-person households are expected to represent 36 per cent of total households in the European Union in 2010, compared to 30 per cent in 1990. Ageing could also mean more time spent at home, higher temperatures in buildings, and wider use of elevators and other electrical devices, therefore increasing electricity and heat uses (albeit partly substituting for transport).

The relation between income and energy consumption is also affected by uncertainties. Transport demand in particular is generally believed to represent a slow-changing share of both income and time. If this assumption is maintained for the coming decades, transport volumes would grow substantially, in line with incomes, while transport times would remain constant. In purely mechanical terms, this would lead to a surge in the use of fast transportation. To the extent that this concerns air travel, such an evolution might considerably aggravate the existing problems of congestion and environmental damage. On the other hand, increased affluence could well lead to higher demands for environmental quality, with all that this implies for consumption patterns and new environmentally friendly technologies.

### *The promise of much-improved end-use technologies*

A major feature of energy consumption in OECD countries in the coming decades might well be the shift from raw fuels to cleaner, more flexible fuels, combined with a move towards more differentiated energy services. As

Martin Bekkeheien *et al.* emphasize in their chapter, new consumer behaviour patterns, boosted by (among other things) regulatory changes, could well be a driver behind this trend, triggering or reinforcing substantial efficiency improvements in end-use technologies, in transport as well as household goods, industrial use, and residential and commercial buildings. In many of these areas, new technologies, often radically innovative, are already available: hybrid petrol-electric engines, direct injection engines, and fuel cells for cars; supercapacitors used in household goods; more efficient electric motors, materials processing technologies and manufacturing processes; high-tech windows, super-insulation, more efficient lighting, advanced heating and cooling systems in buildings. But their development is generally hampered by excessive costs or by the absence of adequate infrastructure. With a fifty year horizon, however, they could represent a substantial market share in energy end-uses.

Fuel cells are an example of promising new technologies; these use hydrogen to provide electricity. The hydrogen fuel can be obtained in different ways, including reforming of coal, oil products or natural gas. Carbon captured during the reform process could even, according to some views, be reinjected in old gasfields in order to accelerate their recovery. Hydrogen in fuel cells is electrolysed by generators, which could ultimately be replaced by direct solar processes. The main rejection by-product of the fuel cell is pure water. According to their advocates, when used in cars, fuel cells already provide higher efficiency and lower maintenance costs than an internal combustion engine.

Apart from the absence of an adequate infrastructure, the development of fuel cells is primarily hampered by their initial costs, which are at least 10 times that of an internal combustion engine. However, the same advocates consider that fuels cells will soon be operational for buildings, because the hot water they reject (at approximately 77 °C/170 °F) can be used to provide heating and cooling services which almost pay for the natural gas input, so that the supply of electricity becomes very competitive. As buildings could necessitate the widespread use (and therefore production) of small units of conversion, unit costs could fall with increased production, so that fuel cells could become more affordable for use in transport. Moreover, the long lifetime and low maintenance needs of fuel cells could make it profitable to use the cars during the time they are parked for providing electricity through the grid. In the United States, for instance, if all cars were totally equipped with fuel cells, this would provide five times the total generating capacity of the national grid. And for each car owner, selling electricity could halve the annual financing and depreciation costs of the car. This example illustrates how, in these innovative sectors, co-ordinated actions of separate actors, including end-users, utilities, industry corporations and policy-makers, might lead to a "jump" in technological change that is much more efficient than a series of incremental changes.

### *The emerging information society and urbanisation trends*

Alongside of these specific factors, energy demand will be affected by globalisation and the transition from the post-industrial to the information society. Most notably, such deep socio-economic changes are expected to lead ultimately to changes in the organisation of work and leisure, in mobility patterns, and in urbanisation trends.

As a result of globalisation and the new international division of labour, some industrial and service activities will continue to shift from OECD countries, and also from newly industrialised countries, to low-wage-cost developing countries. In some developing countries, rapidly growing industrial clusters will generate large urban centres. The number of agglomerations with over 5 million inhabitants in non-OECD countries might be close to 50 in 2010, compared to 23 in 1990. Such evolutions might accelerate the development of utilities and transport infrastructures, and possibly lead to higher-than-expected increases in energy consumption and in environmental problems. It is also possible, however, that as the development process spreads, developing countries may experience a faster shift from heavy industrial activities to lighter industries and to services than usually assumed, resulting in lower energy consumption.

In OECD countries, information and communication technologies will play an essential role in the location of economic activities. The development of telecommunications seems to exert diverse and even contradictory influences on geographic concentration and hence on transport needs. Centripetal forces will likely be linked to economies of scale and aggregation, as modern information technologies allow more flexible and effective management of large economic entities. These forces may be reinforced by broader social trends such as lifestyles that appreciate the 24-hour rhythms of cities. Some authors have also underlined the contribution that new technologies make to the dynamism of urban economic poles, and to their competitive advantage *vis-à-vis* rural zones. Centrifugal forces, on the other hand, result from lower communication costs, which encourage corporations to decentralise part of their activities to less-congested areas where both land and labour are cheaper.

The consequence may be “selective deconcentration”, where future city centres would regroup essential services in which face-to-face contact remains primordial (headquarters of large firms, finance, consulting, etc.), while other activities are relocated in suburban areas and provincial cities. In this context, the metropolitan area could increasingly be constituted of multiple employment centres (multinucleated city), tied together by a complex pattern of people and information flows. Transport patterns would therefore gain in complexity and diversity. On balance, however, the implications for energy use remain equivocal.

## 6. Future developments in supply-side technologies

One of the key findings of long-term projections and scenarios is that the main challenge for technological change in the energy sector is to attain a sustainable development path while minimising transition costs. Achieving sustainability will probably necessitate a mix of various supply-side technologies. In the short term, significant progress could be made in demand- and supply-side efficiency and fuel-switching from coal and oil to gas. In the longer term, however, new technologies are needed. Projections show that it might be necessary to have highly efficient, low-carbon or carbon-free technologies available after 2010/2020 if greenhouse gas emissions are to be reduced without excessive costs.

### *The energy mix of 2050*

To the extent that fossil fuels remain predominant until 2050, advanced and more efficient fossil technologies will be an essential part of future sustainable mixes. The efficiency and environmental acceptability of coal could be greatly improved by gasification and conversion into liquid fuel. Further advances in exploration, drilling and production will be essential to developing the resource base of oil and natural gas. The exploitation of remote reserves of natural gas could be facilitated by progress in transport and the chemical conversion of gas, enhancing security of supply. Technical breakthroughs are also needed to exploit the considerable resources in non-conventional oil, but once again there will be a need for trade-off because of the impact of these new energies on greenhouse gas concentrations.

Nuclear energy could be a significant contributor to sustainable energy mixes providing progress is made with regard to its acceptability, notably by developing advanced reactors with enhanced safety and economic performance, improving nuclear waste management systems, and agreement on the location of waste disposal sites. Renewable sources are expected to gradually gain shares in primary energy consumption in all long-term scenarios, with new high-quality energy carriers ranging from electricity to liquid methanol replacing more traditional uses of renewables. To this end, some of the current technologies such as wind and biomass energy will need to become more cost-competitive, while others – solar energy in particular – have to improve in terms of technical feasibility. However, substantial rises in fossil fuel prices could change this picture. Finally, several possible approaches, including carbon capture and disposal, are still under development.

Electricity generation is also expected to face major challenges in the decades ahead in the OECD area as well as in developing countries, with heavy investment requirements, rising fuel prices, and growing focus on environmental impacts. These will require improved power station efficiency and increased unit modularity and standardization in the construction of new plants, upgrading of old plants, energy source diversification and fuel flexibility, and better control of pollution.

### *A systems approach to long-term energy requirements*

Given the challenges ahead, a strong case can be made for adopting a systemic approach to energy. As Chihiro Watanabe suggests in his contribution to this volume, the aim of sustainable production and consumption can be pursued by choosing the systems option that leads to the most effective combination of efficiency improvement, fuel-switching, and carbon sequestration. That choice leads to a technology package option that can be promoted through a series of actions: eliminating price distortions; ensuring a favourable national context, including appropriate energy security and environmental requirements, enhanced economic competitiveness and availability of finance; developing learning effects and economies of scale; supporting R&D and investment which, in view of the long lead times required for an emerging technology to become operational, must be initiated now; enhancing inter-firm information networks and international co-operation aimed at accelerating technology diffusion in the context of an increasing global interdependence of energy issues.

Systems approaches also imply a consistent policy approach, notably in the fields of infrastructures and network management. For instance, the lack of adequate infrastructures is one important factor dampening the development of new technologies such as fuel cells. Taking full advantage of these cells in terms of efficiency and sustainability would necessitate the building of a hydrogen distribution infrastructure, which may require many years and considerable investment. A more effective solution could be to adapt the existing infrastructures to the requirements of fuel cell-driven cars (by reforming fossil fuels at fuel centres off-board) or, alternatively, to adapt the cars to the existing infrastructures (by reforming fossil fuels onboard). In order to be operational with the existing infrastructure, several projects under development in the car industry have favoured the latter option. The technical option of fuel cells, on the other hand, would mean that fossil fuel reform and hydrogen production would need to be centralised in order to be directed toward other uses and yield economies of scale.

### *A shift to demand-side management*

Finally, as part of a systems approach, the management policy focus might gradually shift from the supply to the demand side. Traditional energy policies have aimed at building supply capacities and infrastructures in order to match projected increases in demand. Increased supply facilities, in return, have probably induced additional demand. Confronted with the high financial and environmental costs of a marginal increase in supply capacity, policy is likely to aim increasingly at influencing demand patterns. End-use energy efficiency could be promoted through tax incentives and support to private projects. Congestion problems could be addressed through a better co-ordination between urbanisation policy, public transport supply and private transport regulation, taking account of the growing diversity of mobility needs. Increasingly privatised utility suppliers might also be more reluctant to develop expensive capacities, and public pricing policies could aim at internalising true social and environmental costs. In short, utilities could evolve in the direction of more flexible network management, differentiating their services between hot network areas (and periods) where demand needs to be calmed, and cold areas where it could be encouraged.

There are indeed already signs that such an evolution may be in prospect, as increasingly the end-user is placed at the starting point of the decision-making process. Decentralised options are spreading as IT systems' capacity to send clear price signals to end-users improves.

## 7. Strategic options for decision-makers in government and industry

The common thread connecting many of the key issues is the question of the respective roles of markets and governments and the necessity to review these in the light of the rapidly changing circumstances in which their interrelationship is likely to be played out in the coming decades. For it would seem that the political, economic, social and environmental context in which energy supply and demand will unfold over the next half-century could be very different from today's. It will probably be characterised by new production and consumption patterns and different communication and information systems, much of this the result of continuing rapid globalisation; modified power structures and new players in the world economic arena – not only countries but also non-government players such as multinational enterprises, NGOs, the scientific community, etc.; and an increasingly evident factor of world affairs: the growing mismatch between the global nature of the issues and the national/local nature of government decision-making.

The broad policy areas and issues can be grouped around five clusters.

A first cluster emerges around the long-term implications of declining conventional oil and gas reserves and of growing concentrations of oil and gas in sensitive regions of the world. The predominant view among energy experts seems to be that, while unpleasant geopolitical surprises cannot be ruled out, availability of resources is unlikely to pose a major problem in the next decades. Two arguments in particular weigh in favour of the prospect of relatively unhampered flows. First, historically the track record in keeping supply lines open even in politically tense periods is good; and second, non-conventional sources would rapidly fill the vacuum created by medium-term disruptions in the supply of conventional resources, though possibly at a higher price. Nonetheless, there will continue to be an important role for governments in the international arena to facilitate openness of energy flows. At least two areas of action stand out as potentially significant for the future in this regard: the creation of continent-wide infrastructural networks of energy supplies (gas, electricity, etc.); and, with a major liberalisation push, the establishment of a global energy market in which energy could be freely traded across the world, thereby diversifying sources of supply and widening the circle of those players with a vested interest in uninterrupted provision of energy supplies.

A second cluster of broad strategic options centres around the functioning of markets and related issues of subsidies, negative externalities and difficult trade-offs. In particular, the question arises of how to resolve the trade-off between, on the one hand, the virtues of clear market signals through the unfettered movement of prices in the energy sector, and on the other, the risks associated with the industry's tendency towards short-term orientations. (Examples of the latter include structural under-investment in long-term energy R&D, and the creation of excessive costs to the overall economy of undue volatility in market prices for conventional fossil fuels.)

More generally, there is the question of how to remove competition-distorting subsidies, and of how to promote the wider use of price signals for creating more efficient gas and electricity consumption patterns, for combating congestion and reducing local environmental pollution, and so on. Although governments have indeed undertaken considerable efforts through negotiation, regulation, etc. to internalise externalities in pricing, there is still ample scope for such initiatives. One example is the idea that governments should provide orientation, guidance and incentives for greater energy efficiency among users by setting long-term targets for energy price increases, *e.g.* through (revenue-neutral) carbon taxes.

While prices and market forces clearly have a pivotal role to play, important future responsibilities for governments can be identified in such areas as setting the rules of the game; using regulations to stimulate and control the operation of competitive markets and to bring about shifts in trends in the economy and society; and keeping up momentum in R&D activities that are not – or not sufficiently – addressed by the private sector. More controversial is the operational role for governments in certain sectors of energy production, in particular nuclear energy. Advocates of an active government role argue that the long lead times and long life spans of nuclear plants, their inherent economies of scale, the stringency of necessary safety regulations and the impact of economic deregulation tilt the playing field against nuclear, making it essential that the public sector remain involved in the construction and operation of plants.

A third set of policy issues concerns the role of infrastructures in the broadest sense. Even in a fifty-year time frame, the slow-moving nature of changes in capital stock, transport and urban infrastructures tends to lock societies into distinct, hard-to-change patterns of travel, work, leisure and lifestyles in general, and to act as a brake on the momentum for transition towards a different energy-environment paradigm. Attention frequently focuses, therefore, on the scope available to policy-makers and business to set infrastructure developments on the right track at the earliest possible stage. In the field of urban and territorial management, for example, one key question is: what mechanisms could be designed to ensure that appropriate policies are in place before developing countries find themselves too far advanced in the urbanisation process to effectively change the trajectory of urban development? In OECD countries, on the other hand, the key questions are rather about how to make cities more adaptable to new technologies and changing energy requirements, and whether it will be possible to have more city-centred development at higher density and with less demand for car travel. Meanwhile, in transport the case is being made ever more vigorously for giving more room to market forces, reducing price distortions and increasing policy transparency. The role of prices in infrastructure construction is crucial in this respect, since appropriate pricing could set the right kind of incentives and disincentives to guide users towards more energy-efficient behaviour.

The fourth cluster of strategic policy issues concerns energy technologies. While technology clearly does not have all the answers to the challenges facing the energy sector, both current and new technologies will nonetheless have a critical part to play in the future. There are several dimensions to this cluster.

The recent long spell of low oil prices has turned the spotlight on R&D. It is generally recognised that in many parts of the OECD area, less money is being spent on research and development in the energy technology field. What is difficult to ascertain, however, is whether this amounts to structural stagnation in R&D activities, or whether lower spending is being at least partially offset by qualitative gains. In many OECD countries much more is being done than before, and being done better and more efficiently. Given these uncertainties, and also in view of the important future role of OECD countries as suppliers and promoters of energy and environmental technologies to developing countries, what can and should governments do to promote long-term R&D?

More questions arise at the commercialisation stage. Three main technological options for the future – renewable, nuclear, $CO_2$ sequestration – are not widely competitive today. They also face very specific constraints, such as the intermittent nature of solar and wind power, the public acceptance of nuclear power, and the technological "unknown parameters" that range from coal gasification to $CO_2$ disposal. Broadly speaking, the same applies to certain other new technologies, *e.g.* fuel cells, super-capacitors for storing electricity, superconductivity, and the exploitation of biological energy systems. In view of all this, how can governments establish a level playing field to allow fair treatment of these options? More generally, the wisdom of "picking winners" remains a contentious issue. Past trends exhibit a strong bias in the sense that the only technologies that have come to the market or been regarded as promising have demonstrated good learning curves, economies of scale and falling costs. This begs the question of how future technologies and their risks should be assessed, and who should bear the risk – public money, private money or a combination of both.

At the technology diffusion stage, the debate revolves around the suitability and viability of specific policy approaches. The problem is to determine the balance to be struck between economic instruments that raise costs in order to reduce consumption; command and control instruments such as mandatory standards; and a combination of end-user empowerment and subsidies that allows the spread of new or improved technologies such as micro-CHP (combined heat and power), heat pumps or fuel cells.

The fifth cluster of issues for decision-makers in government and industry concerns energy and the global environment. Experts' views diverge sharply on whether the obligations of industrialised countries adopted in the Kyoto Protocol will be upheld or not, and on whether stricter, legally binding commitments may be introduced at a later date. While some are confident that Kyoto obligations will be met and that these will serve as stepping stones for further agreements, others clearly doubt this, not least because of the difficulties involved in setting up a viable emissions trading system. Similarly sharp divisions can be observed on whether emissions-trading will in future take off on a grand scale or remain modest in scope. Most contentious of all, perhaps, is the question of the contribution of nuclear power to meeting more stringent environmental standards. Here, the fault lines in the debate follow not one but several issues – the competitiveness, or lack thereof, of standardized serially built nuclear power plants in the future; the enduring problem of public acceptability, especially in view of the risks surrounding the operation of plants, nuclear waste disposal and nuclear proliferation; and achieving greater transparency and clearer accountability as a means of changing public perceptions.

Finally, a naturally recurring, systemic theme throughout the entire debate on the long-term future of energy is co-operation. The key driver is the growing awareness that many new actors will be appearing on the domestic and international stage. The spread of democratic principles, growing decentralisation and heightened individualisation all seem to point to greater power of the individual and less power wielded by governments; to more consensus-seeking across the broad spectrum of stakeholders (users, consumers, NGOs, the scientific community, etc.) on incentives and disincentives, and less autocratic regulation; and to more consultation of consumers, local residents, and other affected parties by public authorities and corporations, and less insular styles of decision-making. At the international level, the emergence of new players, the redistribution of power, and especially the prospect of an ever-increasing energy role for developing countries make it imperative that new and stronger co-operative links be forged between OECD and non-OECD countries across the entire portfolio of energy- and environment-related issues.

# World Energy Prospects to 2020: Issues and Uncertainties

*by*

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## 1. Introduction

To provide a quantitative framework for a discussion of world energy developments to the year 2020, this chapter presents a business-as-usual projection.* The assumption is that pre-Kyoto policies and past relationships between energy consumption, energy prices and incomes continue to hold as they did before November 1997.

If current energy policies remain in place, the outcomes for energy consumption, supply and prices are expected to fall within an uncertainty band around the business-as-usual projection. The main uncertainties concern *i)* the economic and technological drivers of energy demand, *ii)* supply technologies and *iii)* fossil fuel resources.

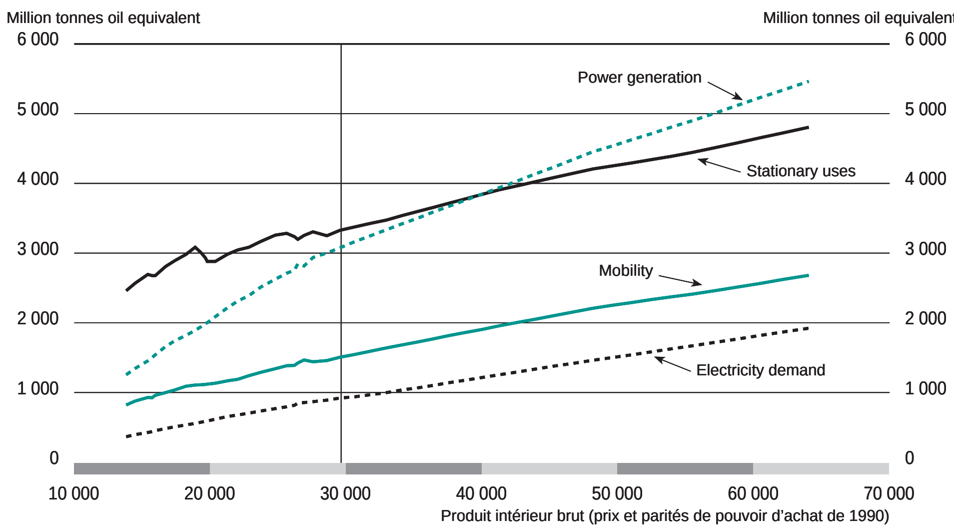
In practice, of course, governments will adopt policies deliberately aimed at preventing the business-as-usual outcome, among them new policies introduced to meet Kyoto commitments to reduce emissions of greenhouse gases for the period 2008/2012. Indeed, the world energy future is likely to differ from business-as-usual. Nonetheless, the projection can provide a useful basis for discussion.

Business-as-usual essentially carries forward past trends in energy consumption and supply on the basis of unchanged behavioural and technological evolutions. A detailed analysis of energy demand has been made for eleven world

* For a fuller expression of this projection, see the IEA publication *World Energy Outlook to 2020,* 1998.

regions; the OECD region is divided into Europe, North America and the Pacific. The transition economies and China are considered separately. The other regions are East Asia, South Asia, Latin America, Africa and the Middle East. The effects of changing economic activity levels on demand are analysed for each region and for each of the main fuels. Where data on fuel prices are available, these are taken into account. Finally, regional trends have been checked for consistency with the trends at world level.

Figure 1. **World energy related services, 1971-2020**




*Source:* Author.

## 2. Trends in demand

Some trends in energy demand have been remarkably stable. Three energy-related services have been identified:

– electricity use and the corresponding fuel input to power generation;

– fossil fuels used for transport – mobility;

– fossil fuels used for heating in buildings and in industrial processes (stationary services).

Fuels used for these three services have closely followed the track of economic activity – gross domestic product – from the time data were first available (1960 for IEA countries, 1971 for the economies in transition and the developing countries) until now. The energy demand analysis indicates that these trends are likely to continue into the future *provided that* energy policies, economic activity and energy prices continue much along the same lines as in the past.

This raises the first major question – whether and to what extent policies will increase end-use energy efficiency beyond what has been experienced since the last oil shock. In the past, downward pressure on energy use grew out of a steady stream of technological improvements that raised energy efficiency, but this was partly offset by upward pressure on energy use from increased incomes and changing tastes. The two vectors result in persistently linear trends. In the future, major new policies will probably be required to change the nature of these relationships.

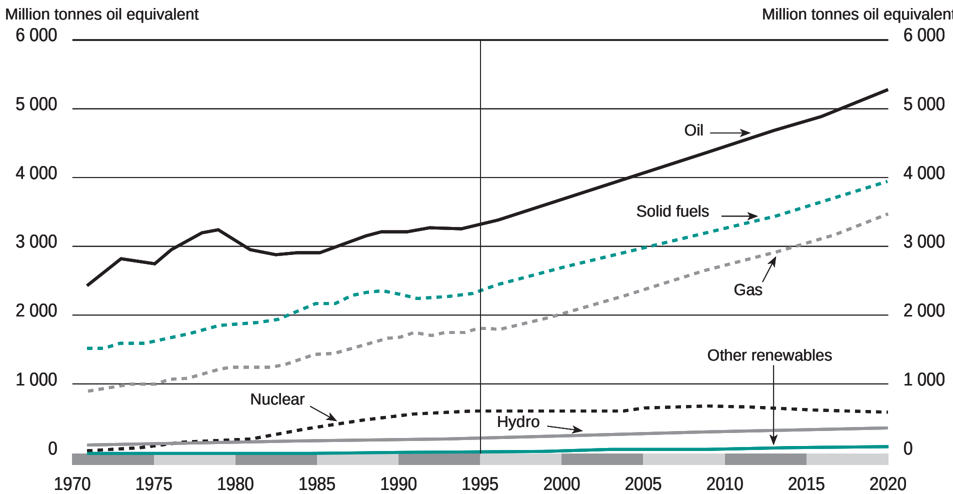
However, there is one major exception – the inefficiencies that exist where markets are distorted or simply do not exist. Should competitive markets or arm's-length commercial transactions be extended to these non-market areas (*e.g.* by removing subsidies which distort prices or introducing sound energy management in public buildings) thanks to regulatory reforms, this would end such inefficiencies and put future trends on a new track. The potential to tap could be significant – as much as 20 to 30 per cent of end-uses forecast for 2020, according to the second assessment report of the Intergovernmental Panel on Climate Change – but the political hurdles should not be ignored.

Non-fossil energy sources are not expected to make major inroads in the market because of their present lack of economic viability (*e.g.* wind and solar) or public acceptance. Demand will continue to be met mostly by fossil fuels. Total world energy demand is projected to grow by around 66 per cent and energy-related $CO_2$ emissions by some 69 per cent between 1995 and 2020, unless new policies are put in place to curb energy use and greenhouse gas emissions.

Oil remains the dominant fuel; gas overtakes coal by 2020; nuclear power remains static; and renewables grow, but their scale remains small. Over the period to 2020, decisions on new nuclear power plants will be made on mainly political rather than economic grounds. For most renewables, site-specific issues and political considerations will dominate economic considerations.

The geographical pattern of energy demand is projected to shift from the OECD region to developing countries; these countries and China are expected to account for 68 per cent of the increase in demand between 1995 and 2020.

Figure 2. **World primary energy supply by fuel, 1971-2020**




*Source:* Author.

## 3. The link to economic growth

As noted above, economic growth is a major driving force for energy use. Faster growth would raise these projections; slower growth would lower them.

The business-as-usual projection has been adopted for the world as a whole: a future rate of economic growth very similar to that over the last twenty-five years – 3.1 per cent annually in real GDP (1990 prices and purchasing power parities).

Drawing on studies of long-run economic growth rates prepared for the OECD report *The World in 2020 – Towards a New Global Age*, published in October 1997, it may be concluded that future economic growth rates depend mainly on:

- future growth in the labour force and its skills;
- future investments and the growth rate of the stock of capital equipment; and
- improvements in overall productivity driven by competition – hence the importance of pursuing regulatory reforms and of introducing competitive markets and arm's-length commercial decisions wherever possible.

It is assumed that developing countries will continue to grow faster than the developed world. But all regions are seen as having lower economic growth rates in the future than they have had in the past. For OECD countries, this is because of falling birth rates and ageing populations; for developing countries, it is because economic growth tends to decline as countries achieve higher living standards. But because the faster-growing countries are gaining larger shares of world GDP, and because growth is gradually picking up in economies in transition, the world economic growth rate remains unchanged.

Slower economic growth in some Asian countries is expected over the next few years as a result of the current financial crisis. Although there is as yet no firm evidence that the crisis will affect long-term economic growth prospects, the necessary regulatory changes are likely to take many years to implement. This will create uncertainty as long as the transition towards the new management style lasts. It is also the reason why lower economic growth rates have been adopted for some of the Asia-Pacific countries.

The rate of future economic growth is particularly uncertain for China and the transition economies.

For China, GDP growth rates since 1978 are thought to be overestimated. The main problems lie in the estimate of the value added of the different sectors (services, agriculture and industry) and in the choice of prices used to assess that value added. Until recently, many prices in China were determined administratively and kept constant over time. Thus the lower costs, margins and real prices achieved in the fast-growing sectors because of the economics of scale were not reflected by a correspondingly lower value added and contribution to GDP.

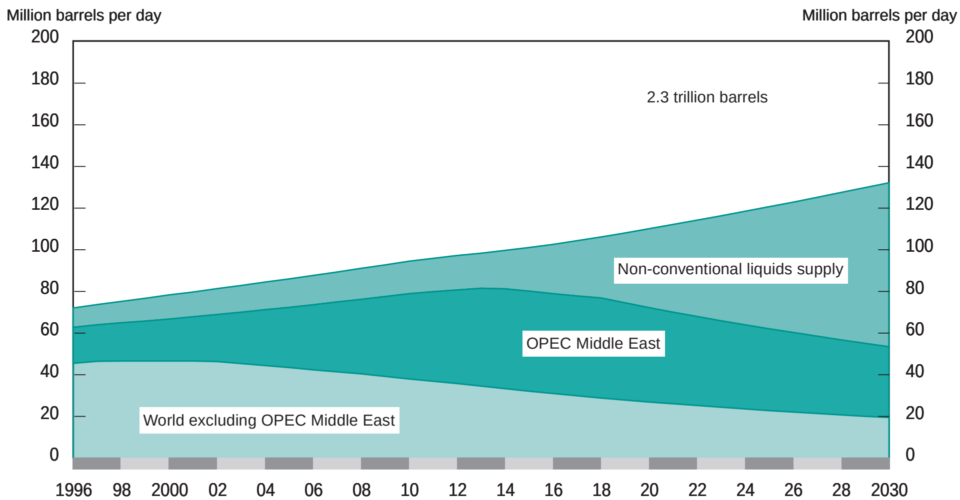
For the transition economies, current estimates of GDP are thought to under-record the true level of economic activity. Official data on GDP suggest that energy efficiency has sharply declined since 1989, but this would be partly offset by the growth of a black or grey economy which could now represent some 40 per cent of the official GDP. It is also difficult to anticipate the future pace of economic reforms and their effects on economic growth and energy demand. As these cannot be estimated from past data, optimistic judgements on these issues have been formed in preparing the projections.

## 4. Implications for energy supply and energy prices

Figure 3 shows world demand for liquid fuels – the solid line – rising at about 1.8 per cent per annum to 2020. This line has been extended at the same growth rate to 2030 in order to assess the implications for oil supply over a longer period.

The size of recoverable reserves of conventional crude oil worldwide is uncertain. The United States Geological Survey in 1993 reported a range of 2.1 to 2.8 trillion barrels. IEA analysis estimates an even broader range, from 2 to 3 trillion

Figure 3. **World supply of oil, 1996-2030**




*Source:* Author.

barrels. These estimates are clouded by two major uncertainties. The first is related to the statistical distribution of undiscovered reserves, the second to the growth factor (to what extent are initial or later reserve assessments underestimated?) and the technology drive (to what degree will the average recovery ratio increase between now and 2050?).

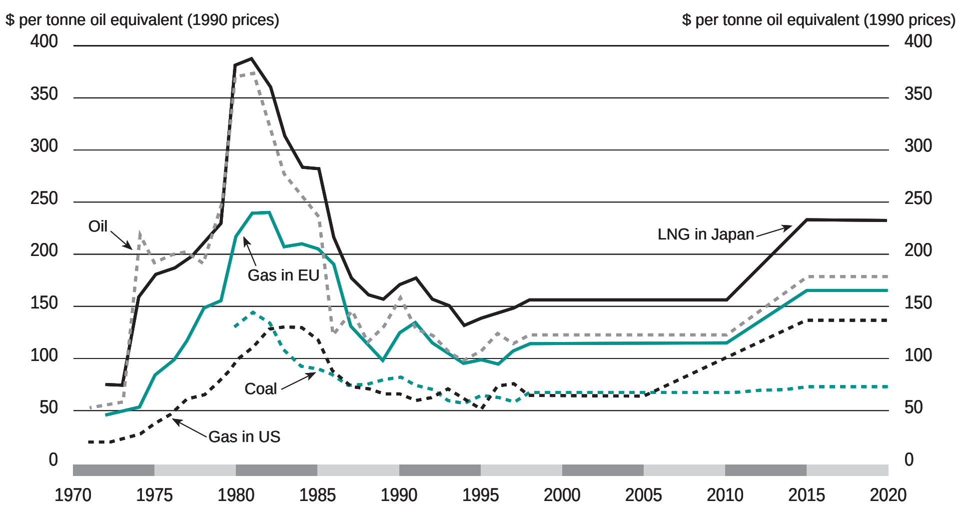
Experience in mature oil regions indicates that oil production builds to a peak and then falls away. In the lower states of the United States, this peak occurred when approximately half the ultimately recoverable reserves had been produced. That same approach applied on a regional basis indicates a peaking of conventional oil production between 2010 and 2020. The timing depends on *i)* assumptions about the level of oil reserves, *ii)* the effects of advances in technology, and *iii)* future oil prices.

Figure 3 is based on an assumption of 2.3 trillion barrels of ultimately recoverable reserves of conventional oil – the most probable value given in the United States Geological Survey study, and the one considered to be the likeliest here as well.

Oil supply from producers outside Middle East OPEC countries is expected to decline after the year 2000. Oil supply from Middle East OPEC producers is expected to peak around 2015. Since the total conventional oil supply will not be able fully to match the demand from an earlier date, additional supplies of liquid fuels are expected to become available from non-conventional sources – mainly heavy oils and tar sands.

No long-term shortage of liquid fuels over this period is expected. But there could be some instability of supply during the changeover to non-conventional sources, especially if concerns about climate change increase the cost of oil. All countries will need to be prepared for disruptions in oil supply during this period.

Figure 4. **Business-as-usual assumptions for fossil fuel prices**




*Source:* Author.

The timing of these events is not the only uncertainty; their impact on fossil fuel prices is a question mark as well. An upward shift of about 40 per cent in the world oil price is indicated – from 17 dollars to 25 dollars per barrel at 1990 prices. In reality, however, it could be larger or smaller – that, too, is uncertain.

Natural gas prices are likely to be similarly affected, because gas competes directly with oil products and because of the increased potential scarcity in some regional markets, *e.g.* North America, before the end of the period. A small upward adjustment has also been made to world-traded coal prices because of the heavy transport costs, mostly relating to heavy fuel oil, included in the coal price.

Fossil fuel prices are not seen as rising continuously over time in real terms – they will be prevented from doing so by "backstop technologies". That could mean non-conventional oil supply, and/or demand-side technologies for individual transportation.

World natural gas production will eventually be constrained by limitation of reserves, but this is not expected to occur before 2020. The OECD Europe and Pacific regions are already importers of natural gas, and these imports are expected to increase. If gas prices in North America remain at their current low levels, gas production in OECD North America plus Mexico could peak during the period 2010 to 2020. Any potential supply shortage in the highly competitive North American gas market would stimulate rises in gas prices. These in turn would lower gas demand and stimulate gas supplies by encouraging additional sources:

- development of non-conventional gas (deep offshore, coal-bed methane or tight gas);
- coal gasification; or
- imports of liquid natural gas (LNG).

The assumption has been made that low-income Asian countries will not import significant quantities of LNG before 2020 because of its high price. In the rest of non-OECD Asia, some countries are exporters and some importers. On balance, non-OECD Asia is not seen as a large net importer of gas. Over the period to 2020, the bulk of gas trade is expected to flow into the OECD Europe and Pacific regions, mainly from Russia and the Middle East, and to a lesser extent from Africa and Latin America.

In the context of highly competitive markets, rising demand for natural gas and oil offers both a great opportunity and a substantial challenge to those countries that possess them:

- The opportunity is to win export markets and earn foreign exchange to provide the basis for economic growth.
- The challenge is to provide an investment climate with a minimum of risks that will promote the inflow of project capital, technology and management skills.

## 5. The environment

The rising use of fossil fuels will place great strain on the environment. Much will need to be done at the local and regional levels to reduce emissions of particulates and acidic gases. Both the technologies and the policies are available, and in use in many countries, for reducing these types of emissions. In general, they are likely to raise costs and limit the future use of fossil fuels. Similarly, the global issue of climate change is likely to have a major impact on energy supply and demand, moving the likely trend away from the business-as-usual projection.

Our projection indicates that unless substantial new policies to promote climate-friendly technologies are adopted to reduce $CO_2$ emissions, the Kyoto commitments will not be met by OECD countries in the period 2008 to 2012. If they are to be met, OECD countries must, either directly or through the flexibility mechanism, achieve reductions of $CO_2$ emissions equivalent to almost 30 per cent compared to what their own emissions would have been in the business-as-usual projection.

If the hypotheses of economic growth and energy efficiency improvements hold, the transition economies will probably meet their commitments by some margin. They must modernise their industries; in doing so, they will become more efficient and switch to less carbon-intensive fuels. But the pace at which these steps will be achieved is in question, as well as the level of emissions likely to be reached in 2008 to 2012.

The increases in $CO_2$ emissions in China and other developing countries between 1995 and 2020 are large – almost three-quarters of the total increase for the world. However, the rapid growth of their stock of capital allows for potential co-operation between IEA countries and these countries.

So far, governments have not chosen the policies they plan to adopt to meet their Kyoto commitments, nor decided what level of international co-operation will be possible. Nor have the effects of individual policies and their interactions been fully studied. For this reason it is not yet possible to alter the business-as-usual projection to show how the Kyoto commitments will be met.

What is possible is to investigate the economic order of magnitude of the actions that energy consumers in IEA countries would need to take to meet the Kyoto commitments regardless of any co-operation with transition economies or developing countries where cheaper opportunities exist.

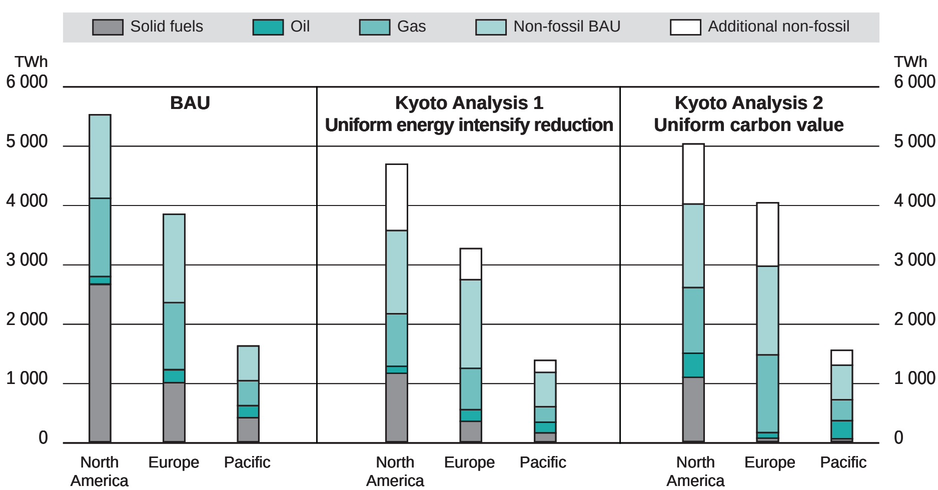
A combination of mandatory increased energy saving in end-uses of 1.25 per cent per annum and replacement of coal use in power generation by nuclear or renewable energy could be chosen. For instance, IEA countries could obtain half of the 30 per cent reduction in $CO_2$ emissions necessary to meet their Kyoto commitments by achieving an additional 1.25 per cent per annum decrease in consumption per unit of GDP over the period 1998-2010.

Based on the elasticities-derived trends over the past thirty-five years, the same reduction in emissions could be achieved by adding a carbon value to fossil fuel prices rising regularly from $0 to $250/ton of carbon between 1998 and 2003. This would raise oil prices back to the level they reached at the height of the oil crisis in 1979. Such a carbon value is high for two reasons. First, the period of around ten years over which reductions in $CO_2$ emissions are sought is short. It does not allow much turnover of capital stock or the introduction of better technologies; it does not provide time for new technologies to develop, nor for the learning process to reduce costs. Second, this analysis makes no allowance for a flexibility that would encourage the adoption of lower-cost $CO_2$ reduction measures in developing countries or transition economies.

Either of these approaches, 1.25 per cent additional end-use efficiency or \$250/t carbon value, would only achieve half of the emissions reduction required. The other half of the overall 30 per cent reductions for IEA countries would, in this illustrative example, be achieved by replacing about half of the coal used in power generation by non-fossil fuel technologies. This is also a drastic departure from the business-as-usual trend in which most new electricity generation plants built are assumed to use natural gas if it is available, and coal where gas is scarce and gas imports are expensive, as in China and India; oil continues to be used as a standby fuel for peak demand or in isolated areas because of the ease with which it can be moved and stored; and only countries with current nuclear programmes are assumed to build nuclear plants in the future.

Figure 5 compares the fuel used in power generation in the business-as-usual case with the result of the Kyoto analyses. Early retirement of a large number of coal-fired plants would be required to replace half of coal-fired power generation in OECD countries by non-fossil technologies to meet Kyoto commitments by 2020.

Figure 5. **Comparison of power by fuel between BAU and Kyoto**
Analyses in 2010 for the three OECD regions




*Source:* Author.

This Kyoto analysis is purely illustrative. But it does indicate that new policies adopted to meet the Kyoto commitments will involve major changes in behaviours that have yet to be determined.

In order to meet Kyoto commitments, developed countries must adopt new policies and measures to achieve lower growth in energy demand and lower carbon content in energy use than is shown in this business-as-usual projection but, in order to lower the overall cost to the economy, they will also need to find ways to tap some of the most cost-effective options existing in transition economies and in developing countries.

## 6. Conclusions

The *World Energy Outlook* and its tentative Kyoto analysis seek to highlight the three main challenges that are going to shape the early decades of the next century:

– The challenges of energy demand: up to now, increasingly freer and more competitive markets have delivered energy at reasonable prices to sustain economic growth. For the future, energy demand shows every sign of increasing: how to go beyond the autonomous and regular energy efficiency improvements demonstrated by the quasi-linear past trends.

– The challenges of energy supply: resources are available – both fossil and non-fossil – but some non-conventional sources will need to be added to the mix. How to cope with the increased reliance on the Middle East and the decline of conventional oil production, with the rising mismatch between the location of gas demand and gas supply, and limits on the maximum amount of fossil carbon that can be released into the atmosphere.

– The challenge of setting the right link between energy supply and demand: how to replace the former central command and control energy systems that have proved ineffective. Attempts to introduce “top-down” decentralisation, *e.g.* independent power producers selling to an unreformed utility, are demonstrating their limits in Asia. Competitive markets are based on the free choice of consumers – hence the need for regulatory reforms to be “bottom-up”, *i.e.* starting from the consumers. They are the ones who pay and they should be “empowered” to choose freely the service they need and the supplier they prefer.

In short, if markets are allowed to work, and if there is a carbon value evident in the market-place, then conditions will be favourable for more climate-friendly outcomes, thanks to a combination of technological and behavioural changes.

# Global Energy Perspectives: 2050 and Beyond

*by*

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## 1. Introduction

This paper summarises a five-year study on long-term global and regional energy perspectives conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC).[1] The paper first gives a short overview of the IIASA-WEC scenarios, and then discusses the relevance of long-term energy perspectives. The discussions of demographics, geopolitics, infrastructure, technology investments and environmental issues that follow illustrate the point that only a long-term perspective to 2050 and beyond can yield insights into possible opportunities and constraints for energy systems development, and associated near- to medium-term policy and entrepreneurial challenges.

## 2. Overview of scenarios

The joint IIASA-WEC study has developed three alternative cases of economic development that are further subdivided into six scenarios of the long-term evolution of the global energy system. The principal focus for all cases is on the period to 2050, but results are also presented to 2100. In brief, Case A presents a future of impressive technological improvements and, consequently, high economic growth. Case B describes a future with less ambitious if perhaps more realistic technological improvements, and consequently more intermediate economic growth. Case C presents a "rich and green" future. It includes both substantial technological progress and unprecedented international co-operation, including major resource transfers from North to South, centred explicitly on environmental protection and international equity. Key characteristics of the three cases are given in Table 1.

Table 1. **Summary of the three cases in 2050 and 2100 compared with 1990**

| | Case | | |
|---|---|---|---|
| | A<br>High growth | B<br>Middle course | C<br>Ecologically driven |
| Population, billion | | | |
| 1990 | 5.3 | 5.3 | 5.3 |
| 2050 | 10.1 | 10.1 | 10.1 |
| 2100 | 11.7 | 11.7 | 11.7 |
| GWP, trillion US(1990)$ | | | |
| 1990 | 20 | 20 | 20 |
| 2050 | 100 | 75 | 75 |
| 2100 | 300 | 200 | 220 |
| Global primary energy intensity | | | |
| improvement, per cent per year | Medium | Low | High |
| 1990 to 2050 | –0.9 | –0.8 | –1.4 |
| 1990 to 2100 | –1.0 | –0.8 | –1.4 |
| Primary energy demand, Gtoe | | | |
| 1990 | 9 | 9 | 9 |
| 2050 | 25 | 20 | 14 |
| 2100 | 45 | 35 | 21 |
| Resource availability | | | |
| Fossil | High | Medium | Low |
| Non-fossil | High | Medium | High |
| Technology costs | | | |
| Fossil | Low | Medium | High |
| Non-fossil | Low | Medium | Low |
| Technology dynamics | | | |
| Fossil | High | Medium | Medium |
| Non-fossil | High | Medium | High |
| Environmental taxes | No | No | Yes |
| $CO_2$ emission constraint | No | No | Yes |
| Net carbon emissions, GtC | | | |
| 1990 | 6 | 6 | 6 |
| 2050 | 9-15 | 10 | 5 |
| 2100 | 6-20 | 11 | 2 |
| Number of scenarios | 3 | 1 | 2 |

Abbreviations: GWP = gross world product; Gtoe = gigatons oil equivalent; $CO_2$ = carbon dioxide; GtC = gigatons of carbon.

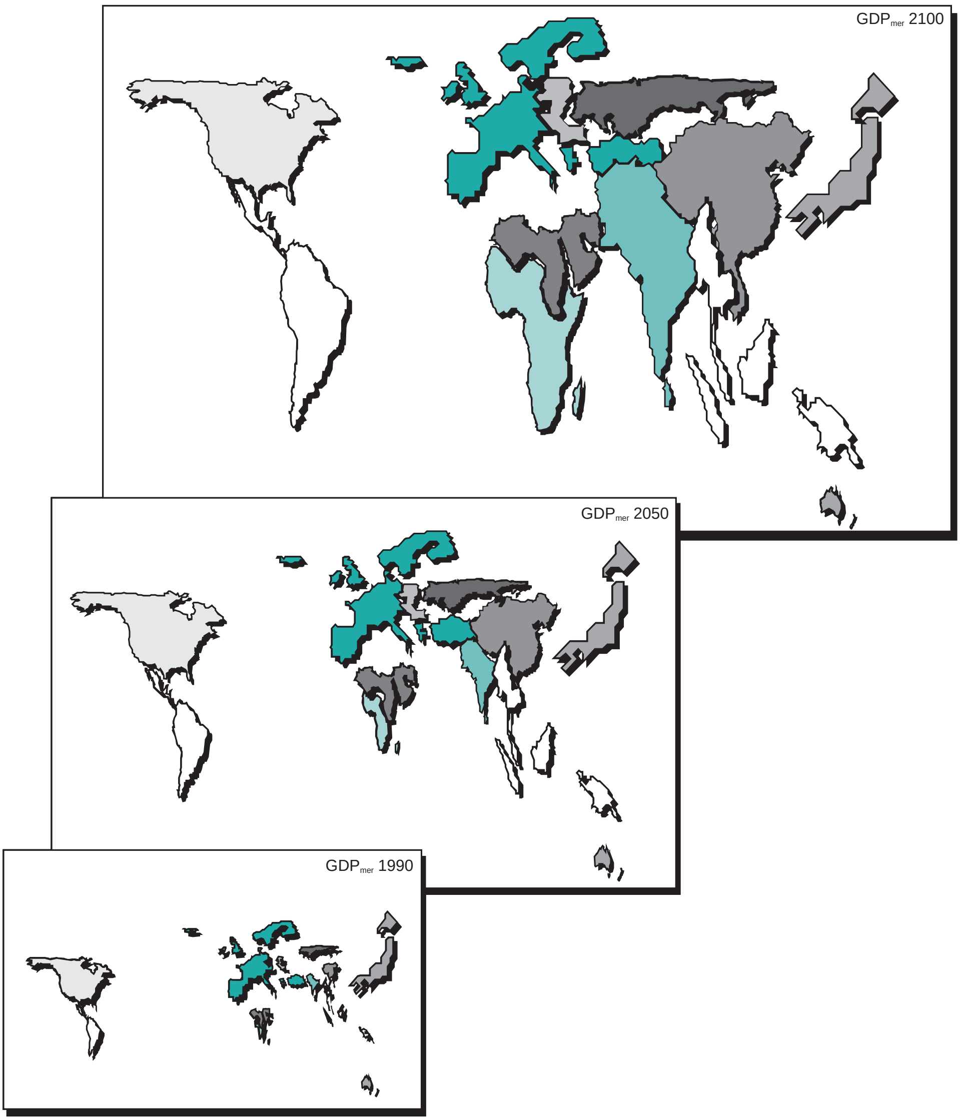
the key message from the long-term scenario exercise is that it is easier to anticipate the forms in which energy will be demanded by consumers in the future than to estimate the absolute level of energy demand, or which energy sources will supply that demand. With increasing per capita incomes around the world, people will seek higher levels of more efficient, cleaner, and environmentally friendlier energy services. Thus, one can see reasonably well the direction in which energy consumers are headed. However, questions having to do with the kind of companies that will supply those services, how, and with which technologies, are wide open.

That central message is robust across a wide range of futures – from a tremendous expansion of coal production to strict limits, from a phase-out of nuclear energy to a substantial increase, from carbon emissions in 2100 that are only one-third of today's levels to increases by more than a factor of three. Yet for all the variation explored, each alternative manages to match the expected demand pull for more flexible, more convenient and cleaner forms of energy. The odds are thus good that consumers will indeed get what they want. Who their suppliers will be, which energy sources will be tapped, the infrastructure that will be involved and the technological means to be deployed all depend on economic development in the world, on progress in science and technology, and on policies and institutions. Those suppliers who make the near-term decisions that prove most effective in pairing up their services with evolving consumer preferences will clearly have the edge.

A second central message from the IIASA-WEC scenario exercise is that over the long term, economic and energy markets will move to today's developing countries. The rates and timing of this move are uncertain (and hence varied across the three cases and their six scenarios), but the overall direction of change is unmistakable: future market growth will be predominantly in the South.

Along with population growth, economic catch-up (*i.e.* of developing countries to the productivity frontier of the industrialised countries, and the resulting catch-up in per capita incomes) implies a long-term shift in the geographical focus of economic activities. Currently the OECD countries, while accounting for less than 20 per cent of the global population, produce and consume close to 80 per cent of global economic output (gross world product measured at market exchange rates). These disparities are illustrated in Figure 1, which rescales the size of eleven world regions in proportion to their 1990 GDP (at market exchange rates). In 1990, the economic map of the world looks highly distorted as a result of current disparities among regions. Most developing regions are barely discernible compared with Japan, Western Europe and North America. Compare, for example, the size of Japan in 1990 with that of China or the Indian subcontinent. For 2050 and 2100, the economic map shown in the figure corresponds to Case B, the Middle Course scenario of the IIASA-WEC study – the most cautious with respect to the speed of the developing world's economic catch-up. Nonetheless, over the long term the economic maps begin to resemble the geographical maps with which all of us are familiar. This means two things. First, economic catch-up is a century-long process and challenge. Some regions may forge ahead but it will take developing

Figure 1. **The changing geography of economic wealth, IIASA-WEC Case B**



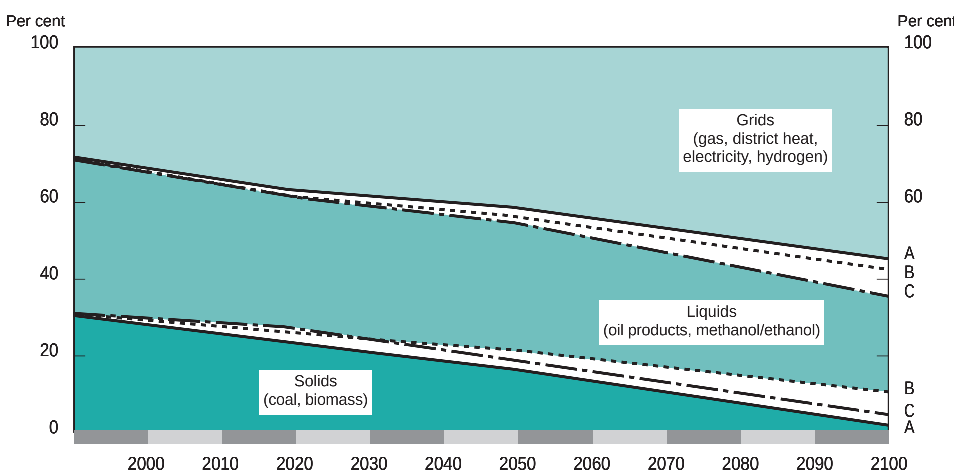

*Note:* Areas of world regions are weighted in proportion to their 1990 GDP levels (expressed at market exchange rates).
*Source:* Author.

countries, in their aggregate, more than five decades to approach income levels characteristic of the OECD countries in the 1960s or 1970s. Second, with long-term economic catch-up, economic as well as energy market growth will occur primarily in the developing world, a point to which this chapter returns in the discussion of the geopolitics of energy use below.

As shown in Figure 2, the pattern of final energy use is remarkably consistent across scenarios. Given rising incomes, all scenarios reflect a continuing pervasive shift toward energy reaching consumers in increasingly flexible, convenient and clean forms. In other words, *quality matters increasingly*. Decreasing amounts of energy are used in an original form (*e.g.* the traditional direct uses of coal and biomass) and increasing amounts reach consumers through elaborate systems of energy conversion and delivery. The overall shift to higher-quality energy carriers and dedicated transport systems, such as pipelines and networks, enhances trade possibilities and promotes similar end-use patterns across regions with fundamentally different primary energy supply structures.

Turning to quantities, *i.e.* levels of energy demand, these are clearly different across scenarios. Rates of economic growth, structural change, technological developments and environmental policies are the four most important long-run determinants.[2] Future levels of energy demand can thus vary widely, even for otherwise

Figure 2. **World final energy by form, in percentage, as solids, liquids and grids**



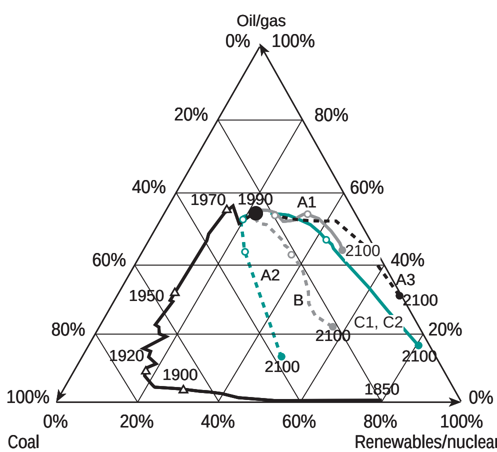

*Note:* Overlapping shaded areas indicate variations across Cases A, B and C.
*Source:* Author.

similar scenario characteristics, in terms of population and level of economic development (Table 1). The IIASA-WEC study expects energy needs to increase one and a half to three times by 2050, and a two- to fivefold increase by 2100. Growth in energy use is moderated by continued improvements in energy intensities. Over the long term it is possible to conceive of huge factor productivity increases throughout the economy (*i.e.* economic growth), but not in the energy sector.

Turning next to the structure of primary energy supply (Figure 3), a significant finding of the study is that there is a wide range of supply structures that can successfully match the persistent final energy trends of Figure 2. Each corner of the triangle in Figure 3 corresponds to a hypothetical situation in which all primary energy is supplied by a single source: oil and gas at the top, coal on the left, and non-fossil sources (renewables and nuclear) on the right. In 1990 their respective shares were 53 per cent for oil and gas (measured against the grid lines with percentages shown on the right), 24 per cent for coal (percentages on the left), and 23 per cent for non-fossil energy sources (percentages at the bottom).

Because of the long lifetimes of power plants, refineries and other energy investments, there is not enough capital stock turnover in the scenarios prior to 2020 to allow them to diverge significantly. But the seeds of the post-2020

Figure 3. **Evolution of primary energy structure**




*Note:* Shares of oil and gas, coal, and non-fossil sources, in percentage; historical development from 1850 to 1990 (triangles) and in the six IIASA-WEC scenarios to 2020 (open circles), 2050 (diamonds), and 2100 (closed circles).
*Source:* Author.

divergence in the structure of energy systems will have been widely sown by then, based on RD&D efforts, intervening investments, and technology diffusion strategies. Decisions between now and 2020 will determine which of the diverging post-2020 development paths will materialise. Rates of structural change in global energy systems will thus remain slow, consistent with the historical experience shown in Figure 3. This puts additional importance on near-term actions that can initiate long-term changes; technology and infrastructure investments are the most prominent examples.

Long-term global energy futures are also no longer seen as geologically preordained. The imminent resource scarcity as perceived in the 1970s does not materialise. With continued exploration efforts and continuing technological progress, accessible and affordable reserves have increased, and this trend will continue to at least 2020. After that all scenarios move away from their current reliance on conventional oil and gas. This transition progresses relatively slowly in Scenario A1, where oil and gas are plentiful. In Scenario A3 and Case C, it progresses more rapidly due to faster technological progress (Scenario A3) or because energy and environmental policies favour the development of non-fossil alternatives (Case C). In Scenario A2 and Case B, the transition away from oil and gas includes an important contribution from coal, whose long-term market share after 2050 ranges between 20 and 40 per cent. Nonetheless, little of this coal is used directly. Instead, it is converted to the high-quality energy carriers (electricity, liquids and gases) demanded by the high-income consumers of the second half of the 21st century. Thus, very different resource and technological options can be drawn upon to meet the drive to cleaner energy demanded by increasingly affluent consumers worldwide.

## 3. Why long-term scenarios?

Only a long-term perspective will allow exploration of possible fundamental changes in global energy systems. Over a period of one to three decades – the usual focus of energy studies – there is neither sufficient catch-up in terms of the South's economic development, nor sufficient turnover of capital stock in the energy sector, to create a situation appreciably different from today's. Over the very long term however, present-day economic disparities will be reduced. Per capita income levels in the developing countries could rise over the long term to levels characteristic of OECD countries today. Similarly, beyond 2050 the entire capital stock of the global energy system will have turned over at least once, offering vast opportunities for radical technological change. This section examines five clusters of variables that are particularly important over a time horizon of five decades or more: demographics and urbanisation; economic development and resulting shifts in the geopolitics of energy use; infrastructure needs; technology; and finally, environmental issues.

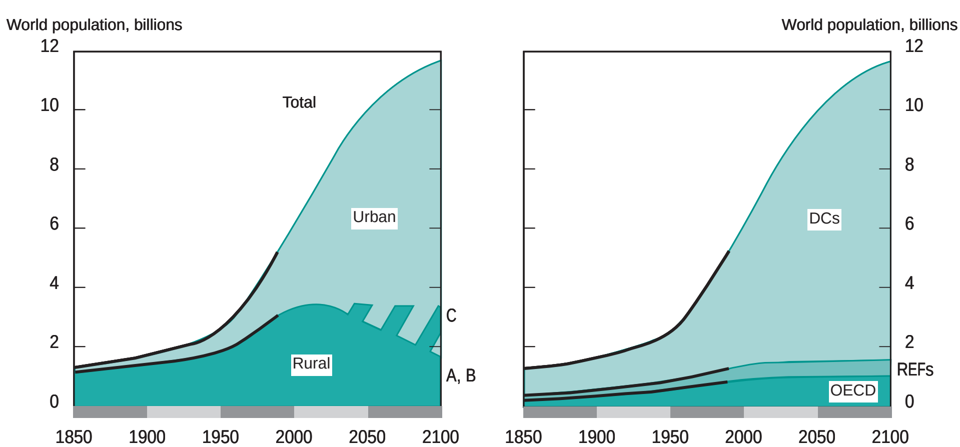
### *Demographics and urbanisation*

The inevitable demographic momentum (the mothers of tomorrow are already born today) makes demographic projections two decades ahead almost certain. By 2020 the global population will number some 8 billion, whether one looks at the projections of the United Nations, the World Bank or IIASA. Going to 2050 and beyond, on the other hand, increases uncertainty – but not uniformly.

When considering global population numbers, the range of uncertainty is somewhat narrower than what conventional wisdom would suggest. Based on the first probabilistic demographic projections made recently at IIASA (Lutz, Sanderson and Scherbov, 1997), demographers ascribe an 80 per cent chance that the global population will number between 9 and 13 billion by the end of the 21st century, which is some 8 per cent higher and 23 per cent lower than the 1992 World Bank figures adopted as central demographic projection in the IIASA-WEC study (Figure 4). More uncertain are two implications of long-run demographic changes. The first one is population ageing, that will first affect the OECD countries (*e.g.* Japan) and then, increasingly, the currently developing countries (*e.g.* China). Little is known about the implications of increasing population ageing on economic growth, or on resource use. The second uncertainty deals with the effect of

Figure 4. **World population development from 1850 to 1990 and the central demographic projection to 2100 used in the IIASA-WEC scenarios**

Left: rural-urban; right: by macroregion




*Source:* Author.

demographic changes, such as a decline in fertility rates, on overall social change and hence possibilities for economic catch-up. Perspectives range between those who argue that population growth hinders economic development (“more mouths to feed”) and those who consider population growth an important driver of economic growth (“more hands to work”). From the perspective of the long-term IIASA-WEC scenarios, the answer is that we do not know. Thus, both scenarios of high or low income growth could be consistent with rapid or slow demographic transitions, although based on current knowledge the odds are higher that fast demographic change (a rapid decline in fertility rates and an increase in life expectancy) is *ceteris paribus* correlated with faster productivity, and hence economic growth.

Conversely, two additional demographic trends can be considered almost as certainties. The first is the concentration of population growth in the developing countries, and the second is urbanisation (Figure 4). The first trend, a critical feature of global population growth, is well known and needs little elaboration. By 2100, the population of the United States, Canada, and the whole of Europe combined drops to less than 10 per cent of the world total – as indeed suggested by all central scenarios of the World Bank, IIASA and the UN, and incorporated into the scenarios of the IIASA-WEC study.

Increasing urbanisation is the second critical long-term demographic feature, frequently ignored in energy studies. More than 80 per cent of the population of industrialised countries live in urban environments, and many developing countries show similar high urbanisation rates. According to the UN, 2.2 of 5.3 billion people lived in urban agglomerations in 1990. Over the next thirty-five years the urban population is projected to increase to 5.2 billion, an amount equal to the total global population in 1990. That increase of 3 billion accounts for nearly all the projected population growth of 3.2 billion to 2025 (United Nations, 1994). Thus, almost all additional global population growth will be urban. According to the UN, 60 per cent of the world's population will live in urban areas by 2025, and, if historical tendencies continue, three-quarters of the global population (approximately 8 billion people) will live in urban agglomerations by 2050. An increasing fraction will live in “megacities” with over 10 million inhabitants. It is estimated that shortly after the year 2000, eight cities will have more than 15 million inhabitants each – and only two of these, Tokyo and New York, are in highly industrialised countries. The remaining six (Beijing, Bombay, Calcutta, Mexico City, São Paulo and Shanghai) are in countries now developing. Providing adequate and clean energy services for a world whose population lives predominantly in urban areas will be a daunting task due to infrastructure (*i.e.* capital) needs and the enormous spatial energy demand densities. And energy carriers will *need* to be clean in order to cease the creation of urban smog from coal and fuelwood fires or the dense motorised traffic that currently plagues most megacities.

### *Development and geopolitics*

Examining demographics in relation to economic development, it becomes clear that there will be a long-term shift in the geographical focus of energy use. In 1990 developing countries consumed 26 per cent of modern energy forms (37 per cent when noncommercial energy uses are included in the statistics). By 2050, the share of developing countries ranges between 58 and 67 per cent, and by the end of the 21st century the range could be between 72 and 83 per cent, *i.e.* a complete reversal of the current energy geopolitical situation.

Figure 1 illustrated how the weight of global economic activity and thus energy use could move South. In fact, most short-term "business as usual" scenarios project faster demand growth in developing countries. But it is important to think through how such shorter-term trends may lead to long-term pervasive changes in energy systems and energy geopolitics, which can only be done by looking to the year 2050 or even beyond.

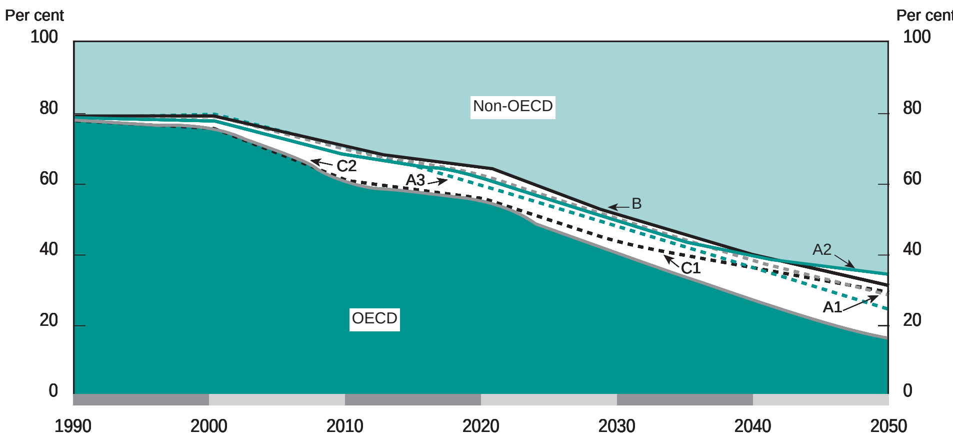
One possible consequence of a major shift in the world's geopolitical energy balance in favour of the developing world could be to increase the ability of those countries to obtain and retain both internationally traded energy forms. Currently, world energy trade is dominated by the energy-hungry importers of the OECD as well as a few large energy exporters. The latter have been the traditional focus of geopolitical energy concerns.

The IIASA-WEC scenarios suggest that over the long term, OECD energy import and security concerns will be shared increasingly by many developing countries. This is illustrated in Figure 5, which shows the relative shares of OECD regions (North America, Western Europe and Pacific Asia) in world energy imports across the IIASA-WEC scenarios to 2050. From that perspective, institutions concerned with long-term energy supply security should indeed look out for new members such as India or China, and foster strategic alliances with major long-term energy exporters like Russia and the Middle East.

### *Infrastructures*

Despite energy globalisation, market exclusion remains a serious challenge. To date, some two billion people do not have access to modern energy services due to poverty and a lack of energy infrastructures. Many regions are overly dependent on a single, locally available resource, such as traditional fuelwood or coal, and have limited access to the clean flexible energy forms required for economic and social development. Policies to deregulate markets and "get prices right"' ignore the poor. Even the best-functioning energy markets will not reach those who cannot pay.

Figure 5. **Share (in percentage) of OECD and non-OECD regions in global energy trade, 1990 to 2050, for the six IIASA-WEC scenarios**

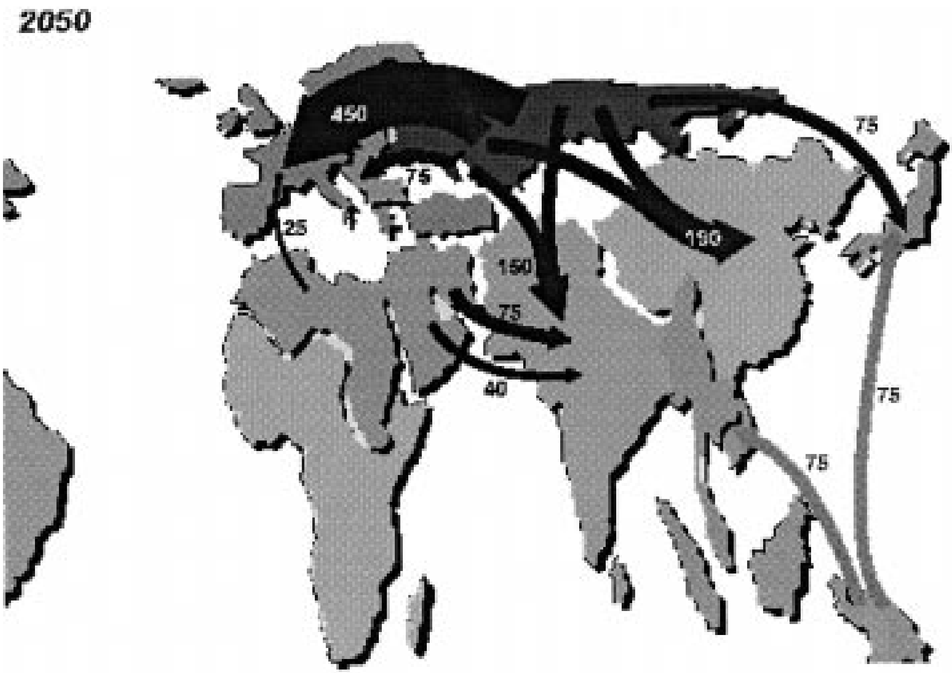



*Note:* Overlapping white area indicates variations across the scenarios.
*Source:* Based on the Internet-accessible IIASA-WEC scenario database (http://www.iiasa.ac.at).

Infrastructures are the backbone of the energy system, and the IIASA-WEC study indicates that requirements for new infrastructures will be vast indeed. Urban and rural poor need to get connected to energy grids in order to have access to modern energy services. New decentralised energy options can help to reduce costs in rural areas, but currently high costs need to be brought down through RD&D efforts as well as stepped-up experience gained in niche market applications. Improved interconnections of energy grids for natural gas and electricity on a continental scale remains a task ahead for many regions, in particular Asia, Latin America, and – in the longer term – Africa.

A recent IIASA study (Nakićenović, 1998) has investigated the energy infrastructure needs in Eurasia based on the demand projections of the IIASA-WEC scenarios. New infrastructures are needed in Eurasia in particular, to match the large available resources of oil and gas in the Caspian region and Siberia with the newly emerging centres of energy consumption in Asia. The trade implications of new energy infrastructures in Eurasia for natural gas in 2050 are illustrated in Figure 6. To put these illustrative trade flows into perspective, gas imports to Western Europe in 1995 amounted to some 90 million tons of oil equivalent (Mtoe), compared to possible trade flows of up to 500 Mtoe (Europe) and

Figure 6. **Natural gas trade within Eurasia in 2050, assuming high demand growth and the availability of transcontinental infrastructure grids**




*Note:* Flows denote pipelines (black) and LNG (grey) routes. Width of trade "arrows" are proportional to gas flows (in Mtoe); areas of regions are proportional to primary energy use in 2050.
*Source:* Nakiæenoviæ, 1998.

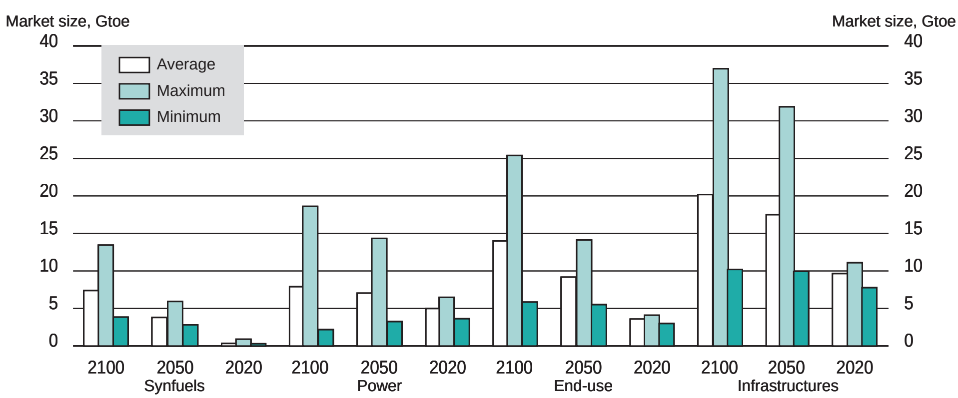
700 Mtoe (Asia) that could be realised with a new continental gas infrastructure (which would take many decades and multi-billion dollar investments to build). Without a long-term perspective, neither the potential nor the realisation horizons of such huge energy infrastructure projects can be studied.

### *Technology*

Technology is the key determinant of economic development and is essential for raising standards of living and for easing the burden humanity imposes on the environment (Grübler, 1998). Technological progress is based on human ingenuity, and is thus a manmade and effectively renewable resource as long as it is properly nurtured. But it has a price. Innovation, especially the commercialisation of novel technologies and processes, requires continual investments of effort and money in RD&D. In turn, technology diffusion depends on both RD&D and steady improvements through learning-by-doing and learning-by-using. Without actual investments and experience there is no long-term technology improvement.

Innovation and technology diffusion require both that opportunities are perceived and that the entrepreneurial spirit exists to pursue them. Long-term scenarios cannot forecast future technological "winners", but they can indicate areas of technological opportunity. Figure 7 illustrates for 2020, 2050 and 2100 the global market potential in the IIASA-WEC scenarios for four classes of energy technologies: synfuel production (from biomass, coal and natural gas); power plants; new end-use energy devices (*e.g.* PVs, fuel cells, heat pumps); and energy transport, transmission and distribution infrastructures. For each of the four classes, the minimum, maximum and average market potential of the six scenarios are shown.

Figure 7. **Global market potentials for four classes of energy technologies: synfuel production, power plants, new end-use energy devices, and energy infrastructures**




*Note:* Minima, maxima, and averages across the six IIASA-WEC scenarios are shown for 2020, 2050 and 2100, in Gtoe.
*Source:* Author.

Across the wide variation in possible energy developments depicted in the six scenarios, the importance of energy infrastructures grows persistently. Even in the low-demand scenarios of Case C, energy infrastructures deliver at least

10 Gtoe per year by 2050. By the end of the century they average 20 Gtoe per year across all six scenarios, reaching close to 40 Gtoe per year in the highest scenarios. The markets for power sector technologies also grow substantially, with a wide spread between the maximum and minimum scenarios. By 2050, the range is between 3 Gtoe per year (energy delivered) and 14 Gtoe per year. This spread relates partly to uncertainties about demand growth, but also partly to energy end-use innovations in the form of new, on-site, decentralised electricity generation technologies such as photovoltaics or fuel cells. The potential for end-use technologies in the long term outgrows that of the power sector. The most important customers for energy technologies would no longer be a limited number of utility managers, but rather millions of energy consumers worldwide. Synfuels also emerge in the long term as a major technology market. An orderly transition away from conventional oil and gas translates into large technology markets for synliquids, syngas, and, in the long term, hydrogen produced from both fossil fuels (coal and natural gas) and renewables (biomass). By the end of the 21st century, the global synfuels market could be at least 4 Gtoe per year, comparable to the current oil market.

As noted above, technological progress has a price – continual investments in RD&D. And all of the technological improvements that occur in the scenarios and that are reflected in the expansion of all categories shown in Figure 7 indeed presume steady RD&D investments. Given the importance of such investment, it is cause for concern that RD&D expenditures are currently declining. The decline is not restricted to any one country or group of countries. It appears to include all industrialised countries, which account for most of the world's RD&D. Private RD&D is declining along with public; private sector investments in energy-related RD&D, for example, have fallen by nearly a third in the United States in the past five years. Evidently, upfront RD&D expenditures are increasingly viewed as too elevated in markets where maximising short-term shareholder value takes precedence over longer-term socio-economic development and environmental protection.

The study's conclusion – that the point of final energy use is where the IIASA-WEC scenarios expect far-reaching technological improvements to occur – carries two additional implications. First, it weakens the argument for extensive RD&D investments in large, sophisticated, “lumpy”, inflexible technologies such as fusion power and centralised solar thermal power plants. Improvements in end-use technologies, where millions rather than hundreds of units are produced and used, are more amenable to standardization, modularisation, mass production and (hence) exploitation of learning-curve effects (read: cost reductions and performance improvements). Secondly, institutional arrangements that govern final energy use and supply are critical. Deregulation and liberalisation of electricity markets can create incentives in this direction as service packages are tailored to various consumer preferences and, especially, as traditional consumers can sell electricity back to the grid. But there are also concerns that liberalisation will discourage long-term RD&D by emphasising short-term profits.

### *Environment*

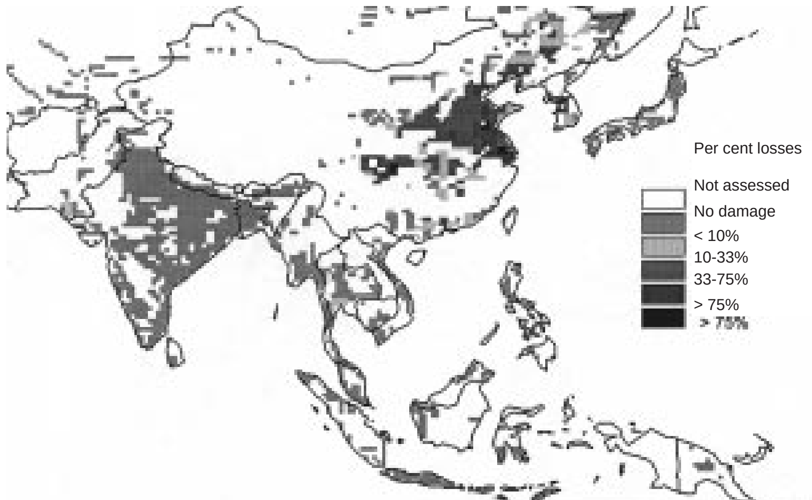
Environmental impacts from energy production and use extend over a variety of spatial and temporal scales: from local to global and from short-term (hours to days in the case of smog episodes) to a century or more in the case of climate change. Even when time scales are very short-term, as in the case of particle emissions in indoor and urban environments in the developing countries, remedying these impacts will take many decades. Policy decisions on climate change are even more intricate. The time scale for massive restructuring of energy systems is up to a century – the time it will take to realise large-scale impacts due to possible climate change. To “wait and see” is therefore clearly not a viable strategy. Conversely, climate change is a long-term environmental issue and needs to be addressed by long-term strategies rather than exclusively through short-term policy measures. In a first approximation for instance, cumulative carbon emissions over the next century matter more than the realisation of short-term emission reductions. Assuring the long-term analytical and policy perspectives required remains a challenge for policies and institutions.

Two representative long-term environmental issues will be discussed here: acidification impacts in Asia, and global climate change.

In the rapidly growing economies of Asia that continue to rely heavily on coal, sulphur emissions and related acidification impacts constitute one of the most important medium-term environmental threats. Left unchecked, $SO_2$ emissions in Asia could nearly triple as early as 2020 and ambient air quality in South and East Asia could deteriorate significantly in both metropolitan and rural areas. Sulphur deposits could reach twice the highest levels ever observed in the most polluted areas of Central and Eastern Europe. One critical consequence relates to food crops in Asia: unabated sulphur emissions would cause critical loads to be exceeded by factors of up to 10, which could result in severe crop production losses over large areas (Figure 8).

Given these results, all IIASA-WEC scenarios assume sulphur control measures. For North America and Europe, the scenarios reflect the most recent legislation to further reduce sulphur emissions – in particular, the 1990 Amendments to the US Clean Air Act and the Second European Sulphur Protocol. For developing economies, particularly in Asia, the scenarios assume gradually phased-in sulphur control measures, particularly for large point sources located in or close to major urban centres. After 2005, any new coal-fired generation in the scenarios incorporates only advanced coal technology, including scrubbers. Sulphur controls are

Figure 8. **Crop production losses in Asia from sulphur emissions in a high-growth, unabatedly coal-intensive scenario (percentage ranges)**




*Source:* Author.

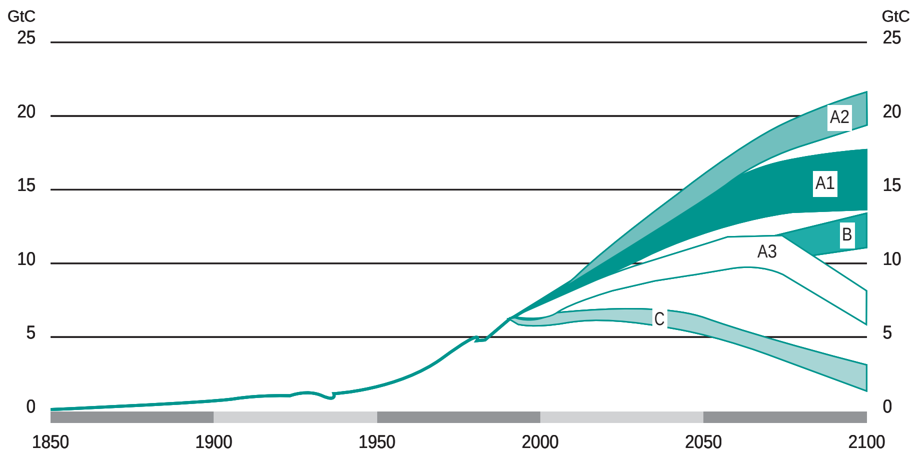
most stringent in the ecologically driven Case C scenarios; they are phased in more gradually in the other scenarios. Even in the former, however, it will take to 2050 before sulphur emissions in Asia return to their 1990 levels. These results suggest that in Asia, concerns about sulphur emissions and their potential regional impact on food security will take precedence over global, long-term environmental issues such as climate change.

Turning to long-term climate change, the magnitude of the stakes depends essentially on two variables: the level of energy use, and the structure of energy supply. Figure 9 shows energy-related carbon emissions in terms of both gross and net emissions from fossil fuels.

Emissions vary substantially among the scenarios; the range is particularly wide in the three Case A scenarios as a function of long-term technology and resource availability. In terms of cumulative net carbon emissions between 1990 and 2100, the Case C scenarios result in less than 540 GtC from energy use. Cumulative net emissions for the other scenarios are 1 210 GtC for Scenario A1, 1 490 GtC for Scenario A2, 910 GtC for Scenario A3, and 1 000 GtC for Case B.[3]

It should be emphasized that emissions in the six scenarios are in most cases below levels of typical “baseline” or “business as usual” scenarios developed within the climate community. Only in Scenario A2 are cumulative (1990 to 2100)

Figure 9. **Global carbon emissions from fossil fuel use, 1850 to 1990, and for the IIASA-WEC scenarios to 2100 (in GtC)**



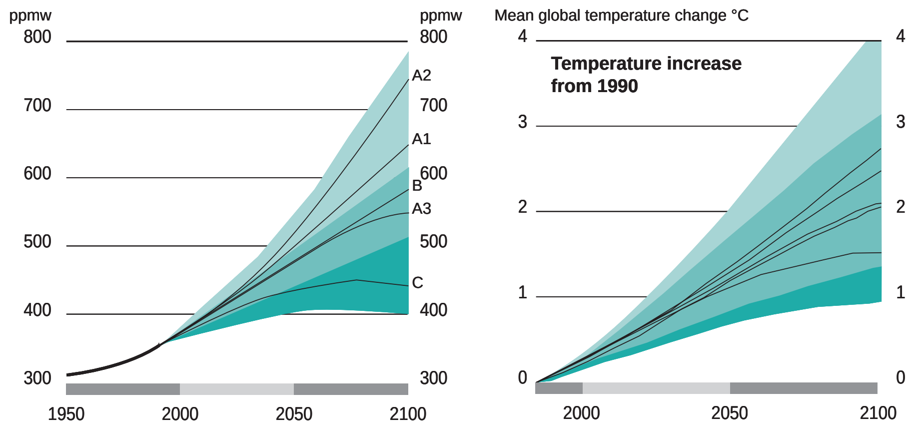

*Note:* For each scenario, the range shows the difference between gross and net emissions.
*Source:* Author.

carbon emissions above those in the IPCC's IS92a reference scenario. The cumulative emissions in Cases A and B lead to central estimates for $CO_2$ concentrations ranging between 550 and 750 ppmv in 2100 (Figure 10). This compares with concentrations of 280 ppmv around 1800 (the beginning of the fossil fuel age) and current concentrations of 368 ppmv. In Case B and in Scenario A1, $CO_2$ concentrations approach 600 and 650 ppmv, respectively, by 2100. The concentrations in the "bio-nuc" Scenario A3 are lower, reaching stabilization at 550 ppmv (assuming declining emission trends continue post-2100), and in the coal-intensive Scenario A2 they are higher, reaching 750 ppmv (continuing to increase post-2100).

Thus, all scenarios except Case C approach the doubling of pre-industrial $CO_2$ concentrations – the basis for most climate model calculations. And, again excepting Case C, all have concentrations continuing to rise throughout the 21st century. (Scenario A3 could reach stabilization at 550 ppmv after 2100.) Based on current knowledge, an increase of $CO_2$ concentrations to 600 ppmv by the end of the 21st century could lead to an increase in the mean global temperature of about 2.5 degrees Celsius and a sea-level rise of up to half a metre.

Despite significant uncertainties that continue to surround the climate change issue, all six scenarios of the IIASA-WEC study confirm that the energy sector is indeed a major stakeholder. In high-growth scenarios, the energy sector alone

Figure 10. **Atmospheric $CO_2$ concentrations, in ppmv – historical development from 1950 to 1990, and in the IIASA-WEC scenarios to 2100**



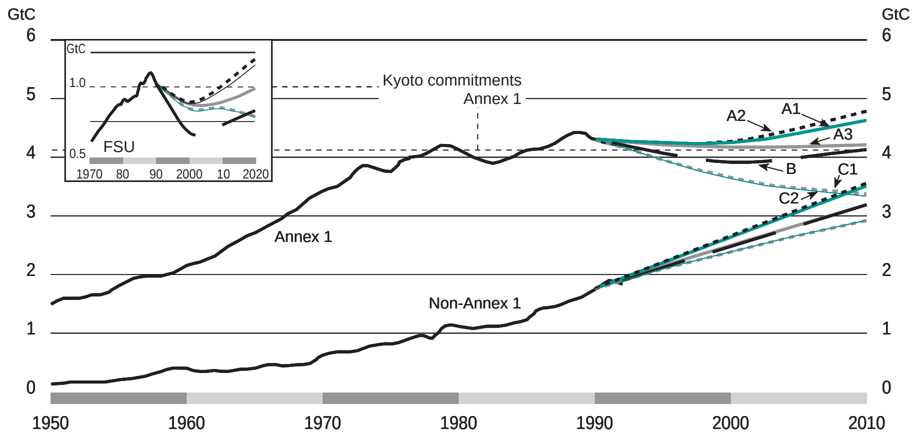

*Note:* Figure on the right shows global mean temperature change compared with 1990, in degrees Celsius. The (substantial) model uncertainties are also indicated.
*Source:* Author.

would account for between 65 per cent (Scenario A3) and 80 per cent (Scenario A2) of all radiative forcing changes due to anthropogenic activities, including deforestation, agriculture, and CFC production and use. Even in the ambitious policy scenarios of Case C, the energy sector – despite drastic action to improve energy efficiency and a resolute move to zero-carbon fuels – would still account for 45 per cent of long-term changes in radiative forcing.

As indicated in Figure 10, however, the scientific uncertainty of such estimates is substantial. In fact, the uncertainty range of possible global mean temperature changes from Case B is so large as to encompass the central estimates of all the other scenarios, from Case C all the way up to (and above) Scenario A2. This clearly illustrates one of the most fundamental climate policy challenges. Scientific uncertainties are in fact so large and time scales so long that little or no policy guidance on short-term emission targets can be provided. Short-term emission reduction targets thus remain essentially political constructs, as exemplified by the Kyoto Protocol.

The principal result of comparing the IIASA-WEC long-term energy and emission scenarios with the short-term Kyoto limits (Figure 11) is that the Case C scenarios are in full compliance with Kyoto, whereas the high-growth, fossil

Figure 11. **Net energy-related carbon emissions, in GtC – historical development from 1950 to 1990 and in the six IIASA-WEC scenarios to 2010**




*Note:* Also shown is the agreed aggregate Annex I emission limit of the Kyoto Protocol. The insert shows emissions in FSU compared with 1990. The Russian Federation's and Ukaine's 1990 emissions equal their Kyoto limits.
*Source:* Author.

fuel-intensive Scenarios A1 and A2 are clearly *not* in compliance. A reassuring finding is that Scenario A3, as well as the Middle Course Case B scenario, can be in compliance with Kyoto, provided full trading among Annex I countries is implemented (*i.e.* full trading of the so-called Russian Bubble is allowed).[4]

This points to another important conclusion that emerges from a long-term perspective. In order to tackle global environmental issues successfully, new forms of international co-operation will be required – first, between the OECD countries and the countries in economic transition, but subsequently also between *all* countries. Without the participation of developing countries, the stated objectives of the FCCC, a stabilization of greenhouse gas (GHG) concentrations, cannot be achieved. The Kyoto Protocol is thus just a first step in a long process towards climate change control. Case C and Scenario A3 illustrate possible strategies for international co-operation to that end. In Case C, environmental policies are directly linked to issues of international economic equity, leading to substantial resource transfers from North to South targeted at sustainable development, energy conservation and low- and zero-emission energy systems. Scenario A3 relies less on new models of international economic co-operation; it instead describes a pathway of "orderly transition" away from the current dominant reliance on fossil fuels through accelerated technological change. But here again, substantial near-term, upfront investments are required to further RD&D efforts and to provide for the learning effects in new energy technologies that are necessary to render those technologies competitive in the long run. Such a scenario could become feasible if, for example, revenues from emissions trading under the Kyoto Protocol are invested prudently in post-fossil technologies and infrastructures. Explicitly dedicating revenues from emissions trading to such long-term environmental purposes might also make both emissions trading and resource transfers more politically acceptable in the short term.

## Notes

1. That study, published in book form, is the source of all figures in this chapter unless otherwise specified: N. Nakićenović, A. Grübler and A. McDonald, editors (1998), *Global Energy Perspectives,* Cambridge University Press.
2. Energy prices are an important determinant for the short-to-medium term. In the long term however, technology and policy are more important determinants, although important feedback mechanisms exist, *e.g.* in the form of induced technical change.
3. Cumulative gross emissions vary from below 630 GtC (the Case C scenarios) to 1 140 GtC (Case B) to between 1 070 (Scenario A3) and 1 630 GtC (A2).
4. "Russian Bubble" refers to the difference between the required Kyoto limit (stabilization at 1990 emission levels) and actual emission levels that have declined precipitously with the economic depression in countries undergoing a transition to a market economy.

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# Towards a Sustainable Energy Future

*by*

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## 1. Introduction[1]

Doomsday predictions are fading from the energy debate. They came mainly in four forms: depletion of fossil fuel reserves; radioactive pollution from accidents in nuclear energy production; use of nuclear weapons as a result of proliferation engendered by nuclear energy production; and catastrophic climate change resulting from burning fossil fuels.

Claims that we will run out of oil and other fossil fuels in the near future have been made several times, but not substantiated. The drastic price increases of the first oil shock – seen by some as first signs of limits to growth – have been reversed, and in the meantime huge additional reserves have been discovered. Severe accidents in nuclear power plants have happened, most notably in Chernobyl, but people continue to live near such plants all over the world. Nuclear proliferation is a serious issue, and by no means only from military sources, but even the bombs ignited by India and Pakistan found less media coverage than, say, a soccer world championship. Finally, climate change is now firmly on the agenda of international environmental diplomacy, and the media present amplified El Niño phenomena as images of disruption from climate change. Nevertheless, neither the current scientific consensus nor current public opinion is pushing governments to pursue a global climate policy that would reduce carbon emissions in the coming decades.

So, are we back to business as usual? North Americans use commercial energy at a rate[2] of about 10 kilowatts (kW) per head, Europeans at about 5 kW, inhabitants of newly industrialising regions at about 2 kW and the large majority of humankind at considerably lower rates. The current world average is 2 kW, but it is likely to increase as billions of people get a chance to emulate the American way of life. Fifty years from now, the global average may well reach 3 kW per head, and the population may double. Commercial energy use would then be three times as high as today.

Currently, 95 per cent of commercial energy production is based on fossil fuels. While oil still plays a pivotal role, its gradual replacement by gas is already under way. In the longer run, coal and other sources of fossil fuel may take over. Bringing the costs of other sources of commercial energy down to levels that would make them competitive with fossil fuels would appear to be tremendously difficult. Business as usual, therefore, may be characterised by prolonged reliance on various categories of fossil fuels. In the more distant future, changeovers to other sources such as solar or fusion may take place as well.

Received wisdom has it that such switching would be triggered mainly by price increases, signals that prevailing energy sources are increasingly scarce. According to this view, oil prices are at some stage bound to increase as easily exploitable reserves are depleted. As a result, technologies to exploit other reserves will be improved, and other energy sources, *e.g.* gas or biomass, will sooner or later become competitive. In this panglossian world, energy crises are a thing of the past; the invisible hand of the market will reliably take care of energy provision in the near and distant future.

The present paper argues that such an approach of benign neglect is inappropriate, for two reasons. First, it would drastically reduce the degrees of freedom of the global energy system in the decades to come, and so render it vulnerable to serious disruption. And second, it would miss huge business opportunities, which can be realised if the global energy system enters a different trajectory.

The next section analyses the relationship between the present global energy system and the environment. The former includes all aspects of energy supply and use. Environmental aspects are discussed in the broader context of sustainability, *i.e.* in terms of the long-term compatibility of human activities with respect to ecological, economical and social issues. Deficits are classified according to their temporal and spatial dimension as well as with respect to possible avoidance strategies.

Section 3 confronts humankind's long-term energy needs with the long-term constraints implied by the conditions for a sustainable energy future. It is shown that gradual changes, *e.g.* improvements in the cleanness and efficiency of certain energy production or utilisation methods, though important, are insufficient to reach a sustainable energy system within the next fifty years.

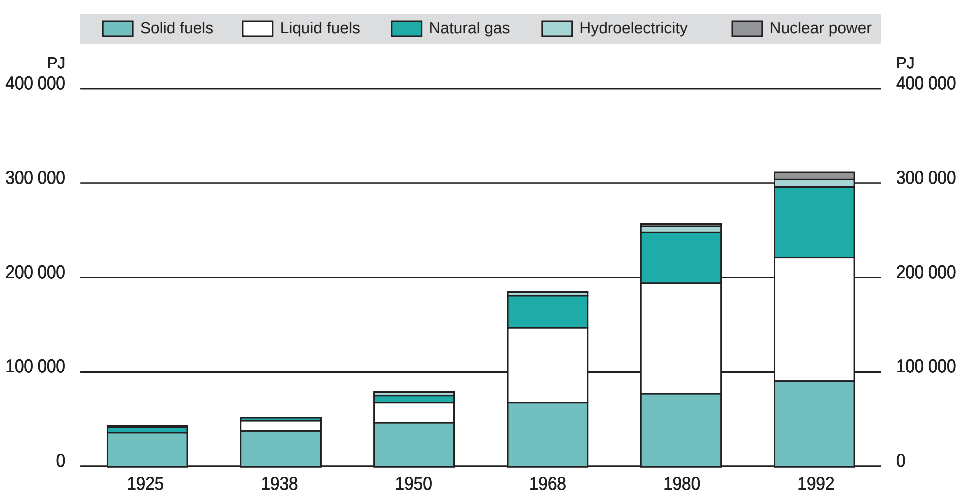
The potential and priorities for non-marginal changes are discussed in Section 4, which defines sustainable level of energy utilisation per capita and shows how energy can be produced at this level. The analysis examines environmental issues and socio-economic factors in line with the definition of sustainability adopted, and presents policy options that allow decoupling – within certain limits – of the level of energy utilisation from industrial output, *i.e.* from wealth and quality of life.

## 2. Environmental aspects of the present energy system

From 1950 to 1992, global consumption of commercial primary energy has increased from 76 500 PJ to 311 000 PJ, *i.e.* by a factor of four (Figure 1). Between 1950 and 1968 the average annual growth rate was 4.9 per cent; it then dropped, to 2.4 per cent by 1992. That year, 95 per cent of primary energy consumption was based on fossil fuels. Nuclear and hydropower contributed 2.5 per cent each.[3] Other energy resources, such as biomass, solar, wind, tides, and geothermal, are either negligible in a global context or are not listed as commercial resources (*e.g.* firewood in developing countries); in total, they add another 6 per cent to global energy consumption (Table 1).

Figure 1. **World energy consumption**

Temporal development of annual global consumption of commercial primary energy between 1925 and 1992. 1 PJ = 1 petajoule = $10^{15}$ joules




*Source:* Enquête-Kommission (1995), “Schutz der Erdatmosphäre” of the Deutscher Bundestag, Economica Verlag, Bonn.

Table 1. **Yearly global primary energy consumption (1993)**[a]

| | Total | Non-commercial[c] | Changes since 1973 of commercial energy | Per capita: Total energy | Per capita: Changes since 1973 |
|---|---|---|---|---|---|
| | (EJ/year)[b] | (% of total) | (%) | (Watt)[d] | (%) |
| World | 345 | 6 | +49 | 2 000 | +6 |
| Africa | 13.6 | 35 | +144 | 650 | +41 |
| Ethiopia | 0.46 | 90 | +104 | 290 | |
| Nigeria | 1.7 | 59 | +420 | 530 | +221 |
| Asia | 104.7 | 9 | +185 | 990 | +82 |
| China | 31.7 | 6 | +179 | 860 | +110 |
| India | 12.1 | 23 | +258 | 420 | +128 |
| Japan | 17.5 | ~0 | +41 | 4 600 | +24 |
| Sri Lanka | 0.17 | 55 | +71 | 290 | +15 |
| Europe | 109.6 | < 1 | +90 | 4 800 | +73 |
| United States | 82.7 | 1 | +13 | 10 300 | –7 |
| Canada | 9.3 | 1 | +47 | 10 400 | +12 |

*c)* From *World Resources* 1996/97, World Resources Institute.
*d)* 1 EJ = $10^{18}$ Joules.
*e)* Traditional fuels such as firewood, animal waste, etc.
*f)* 1 Watt corresponds to 32 million Joules per year or 8.8 kWatt-hours per year.

The average total (commercial and noncommercial) energy consumption per capita strongly varies between developing and developed countries. According to the examples given in Table 1, noncommercial energy, which is mostly renewable, can reach 90 per cent of total energy consumption (Ethiopia), but is only significant in countries with per capita energy consumption smaller than 1 000 watts. Due to the limits of noncommercial energy resources in these countries, any substantial increase in energy demand can only be satisfied by commercial energy.

The production, distribution and consumption of energy are accompanied by numerous environmental impacts that differ widely in severity. Some are system-inherent, others are avoidable through adequate technical and organisational measures. Although these measures may significantly increase the price of the affected energy resource, avoidable impacts are not considered insurmountable with respect to the future exploitation of the corresponding resource. Furthermore, it is important to make a distinction between local and global impacts. The most important impacts of the principal energy resources today (fossil fuels, nuclear, hydro) are summarised in Table 2. A similar table could be composed in which the impacts are not sorted according to energy resources but according to the human activities linked to the consumption of energy, such as housing, supply of food and water, mobility, and production of consumer goods.

Table 2. **Environmental impacts of the present energy system**

| | Inherent | | Avoidable | |
|---|---|---|---|---|
| | Global | Local | Global | Local |
| Fossil | | | | |
| Coal | $CO_2$ | Mining (surface) | Acid rain | Air pollution |
| Oil | $CO_2$ | | Ocean pollution | Air pollution, local water resources |
| Gas | $CO_2$ | | Greenhouse gases due to leaking pipelines | |
| Hydro-power | | Aquatic ecosystems/ competition with other water usage[a] | | Aquatic ecosystems/ competition with other water usage |
| Nuclear | Non-proliferation | Accidents/political stability | | Radioactive waste |

*a)* If a substantial fraction of the total estimated capacity of hydropower production (about 50 000 PJ per year) were to be implemented, the interference with aquatic ecosystems would become a global problem. Today's production is 7 600 PJ per year.

The widely supported perspective of sustainable development (see, *e.g.*, OECD, 1997) offers the opportunity to develop a number of suppositions about the environmental dimension of the present global energy system. The following points merit special attention with respect to sustainability:

*a)* The system is predominantly based on non-renewable resources (fossil fuels).

*b)* The salient discrepancy between the geographical distribution of the major oil and gas resources and the present distribution of energy consumption indicates a latent danger to the stability of the global economic system (Figure 2).

*c)* The system is inherently linked to the increase of atmospheric $CO_2$ and thus to accelerating perturbation of the global climate system. The local and global consequences of this perturbation are still unknown in detail, and will probably never be fully predictable.

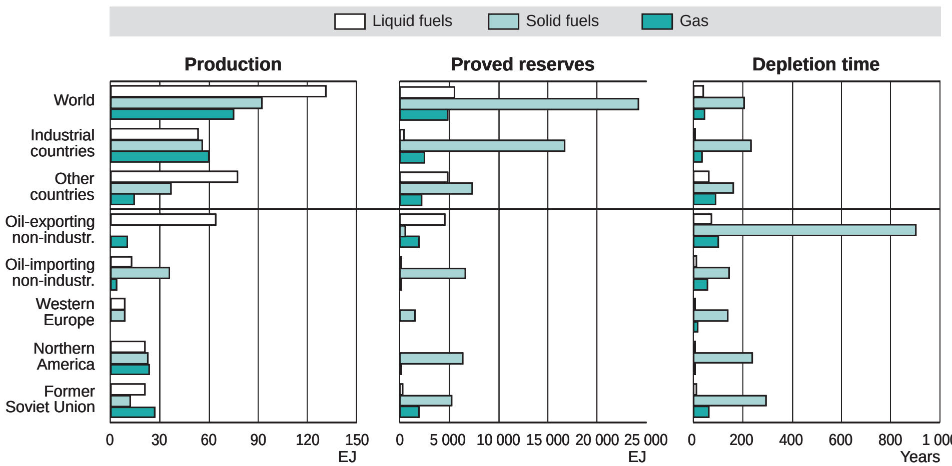
*d)* Average per capita energy consumption varies by more than a factor of 20 between industrialised and developing countries (Table 1).

*e)* To date there is still no convincing and politically accepted solution for the treatment and storage of nuclear waste, in spite of enduring and costly efforts in different countries. This problem would increase drastically if nuclear energy were to play a significant role in the future global energy system.

Each of these points is discussed briefly below.

Figure 2. **Commercial primary energy: production, reserves, and theoretical depletion time**

1 EJ = $10^{18}$ joules




*Sources:* World Resources Institute: Internationaler Unweltatlas, *Jahrbuch der Umweltressourcen*. Band 6, Ecomed, Landsberg/Lech, 1995; UN Energy Tape, New York, 1991, 1993; *World Energy Council, Survey of Energy Resources,* London, 1992.

### *Fossil fuels as non-renewable resources*

The decades that have passed since the first report of the Club of Rome, *Limits to Growth*, have taught us that resource limitations are not absolute and that the rate of exploration of new resources may sometimes exceed the rate of exploitation of known ones. As a result of this lesson, there is now a danger of adopting the opposite view, *i.e.* that resources such as fossil fuels are eternal. Even if present production rates were kept constant in the future, the known and economically exploitable reserves of oil and gas would last only another half century (Figure 2). Coal reserves would last 200 years or longer, but that time could shrink if, as predicted by several models, the rate of energy consumption increases. Inevitably, estimates of available resources involve huge uncertainties – and assuming that all uncertainties will be resolved in the most favourable way is rarely a wise approach to risks.[4]

Given the fact that present energy needs are built into our existing infrastructure (buildings, transport networks, production facilities, etc.), basic changes in the world's energy system are extremely slow. Furthermore, the absolute level of global energy consumption is nearly twice as high today as it was around 1970, when *Limits to Growth* was published. At this higher level, the relative importance of any new resource must generally become smaller. In other words, changing course in the face of new challenges and opportunities becomes more and more difficult as the business-as-usual trajectory is pursued further. As the level of consumption increases, the "time of safe practice", *i.e.* during which our present policy (or practice) can be sustained without severe problems, is correspondingly reduced. And the principle of constant time of safe practice warns that the development of alternative strategies and new resources should at least keep pace with the exploitation of land reserves and resources (Imboden, 1993).

### *Discrepancy between the geographical distribution of resources and consumption*

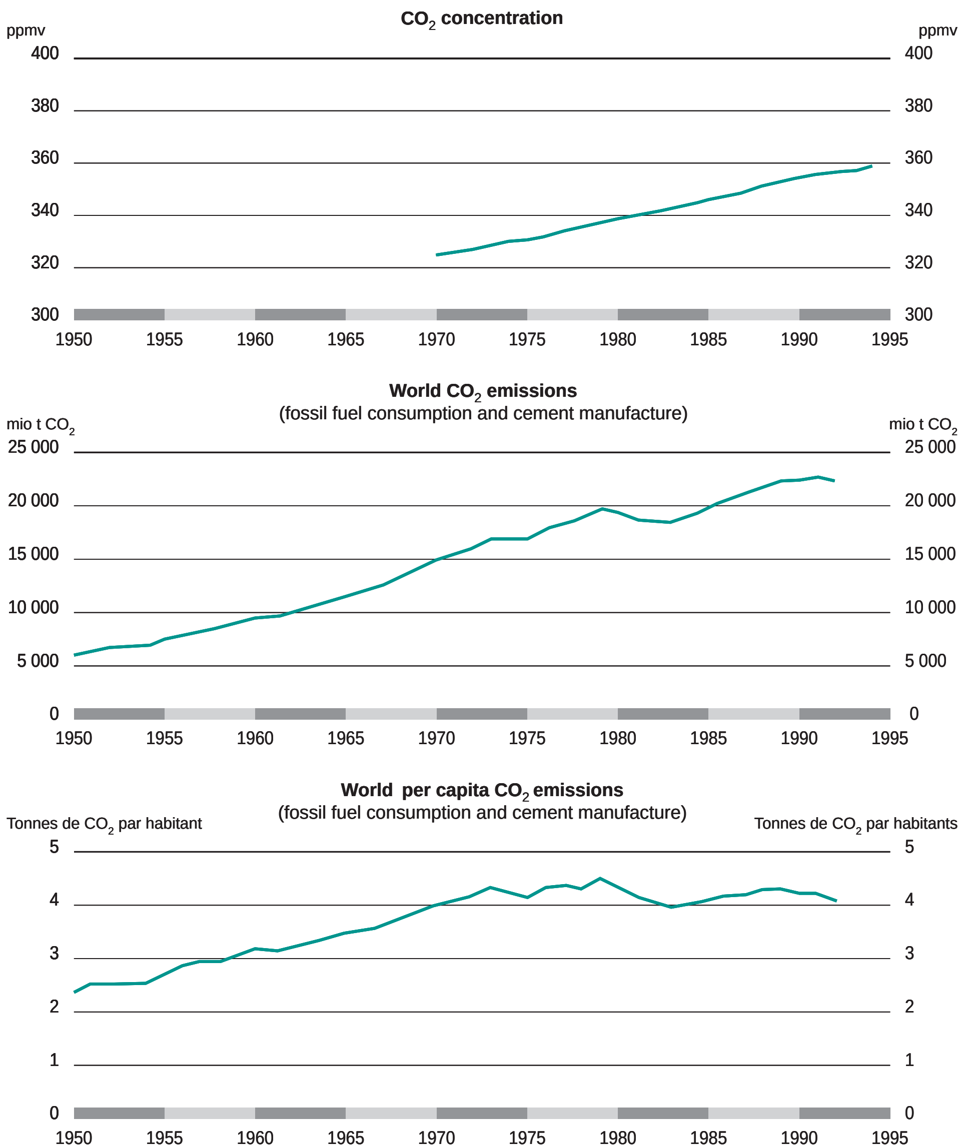
From a global perspective, Figure 2 seems to yield enough time for the development of a new global energy system – if this endeavour is initiated now. But things look even more worrying on a regional level. The resource life expectancy of oil and gas in most industrialised countries endowed with such resources is only ten to twenty years. Estimates of fossil fuel reserves are notoriously controversial, but in the recent literature a strong case has been made that cheap oil reserves will be increasingly hard to find in the future, with gas offering a respite of only a few decades. The situation is less severe for coal, but a major shift to coal would significantly increase the production of atmospheric $CO_2$ per energy unit (see below).

### *The increase of atmospheric $CO_2$*

Basic information regarding the anthropogenic impact on the atmospheric concentration of $CO_2$ is summarised in Figure 3. Present total $CO_2$ emission is about 22 billion tons per year. It is probably too early to fix conclusively a sustainable emission target. According to the studies of the Intergovernmental Panel on Climate Change (IPCC), however, total emissions must begin to decrease in the next two decades in order to achieve constant $CO_2$ levels one to two centuries from now. Since global population will continue to grow during this time, per capita $CO_2$ emissions will have to decrease that much more dramatically.

For example, if atmospheric $CO_2$ levels should not exceed the value of 450 ppmv (about 60 per cent greater than the pre-industrial level of 280 ppmv) in the long run, total emissions would need to fall to about 10 billion tons in the year 2050 (Table 3). With an expected population of 10 billion, that figure corresponds to about 1 ton of $CO_2$ per capita and year (compared to nearly 4 tons today) – which translates into an average energy use per capita of about 300 watts if the energy is completely produced from coal, or 600 watts from gas. In contrast, most models predict total $CO_2$ emissions to increase by a factor of two or more. This discrepancy illustrates the dilemma linked to the problem of global climate change.

Figure 3. **Atmospheric $CO_2$ concentration and anthropogenic emissions since 1950**




*Source:* Brown *et al.*, 1995.

Table 3. **The global $CO_2$ situation**

| $CO_2$ emission per capita and year[a] | | |
|---|---|---|
| World average | 4 | t $CO_2$ p.p. and year |
| United States | 21 | |
| OECD countries | 12 | |
| India | 0.7 | |
| Total emission 1992 : | 22 000 | million tons per year |
| Green scenario 2050: | 67 000 | |
| Sustainable scenario 2050: | 10 000 | |
| Steady state (after 2100) : | 7 000 | |

Permitted emission per person and year[b]

| | Population (billion) | Emission (t p.p. and year) | Possible energy production by: Coal (Watt/person) | Possible energy production by: Gas (Watt/person) |
|---|---|---|---|---|
| Sustainable 2050 | 10 | 1.0 | 300 | 600 |
| Steady-state 2100 | 12 | 0.6 | 200 | 400 |

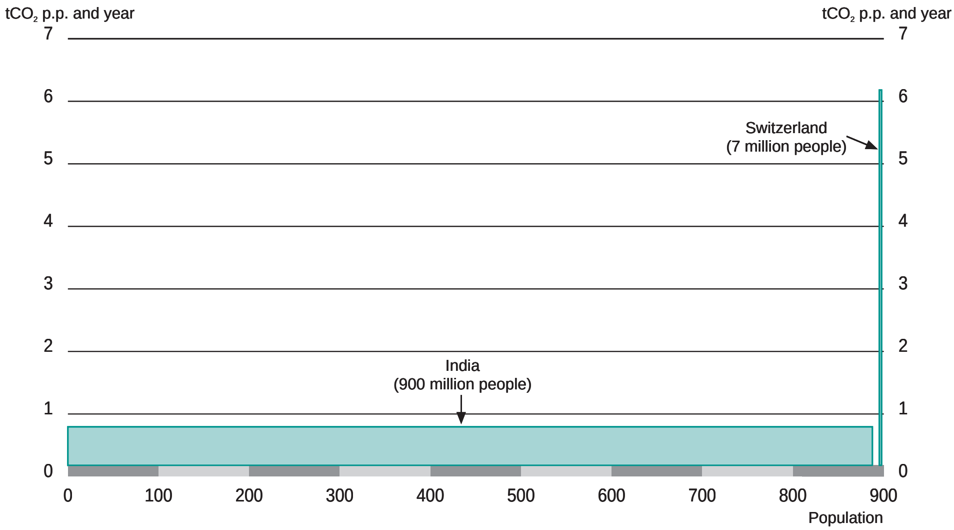
*a) Source:* OECD (1995), *Global Warming: Economic Dimensions and Policy Responses*, and IEA, Energy Statistics, www.iea.org.
*b) Source:* "Climate Change 1995", IPPCC Report of Working Group, WMO/UNEP.

Obviously, humankind may incur self-made climate change, and it is quite possible that for the next few decades this will not lead to huge economic damages in OECD countries. On the other hand, enough extreme weather events could be expected to trigger a public opinion response of far greater proportions than, say, the one triggered by BSE. And in the course of the next century, a business-as-usual strategy is likely to affect large parts of the world, inflicting damage such as sea level rise, desertification, and huge disruptions of global climate patterns. In many cases, specific effects of fossil fuel burning will be detectable only at a stage where it will be too late to avoid them.[5]

### *The heterogeneous pattern of current global energy consumption*

Average per capita energy consumption rates vary greatly among countries (Table 1), as do $CO_2$ emissions (Table 3). This is illustrated in Figure 4, which compares the emissions of two very different countries, India and Switzerland. It is highly unlikely that these huge differences in energy use will persist. Thus, two basic alternatives lie ahead. On one hand, global energy use may increase by a factor of three or more as developing countries eventually raise their energy consumption to the present level of at least the European countries (about 5 kw

Figure 4. **Comparison of $CO_2$ emissions of India and Switzerland**



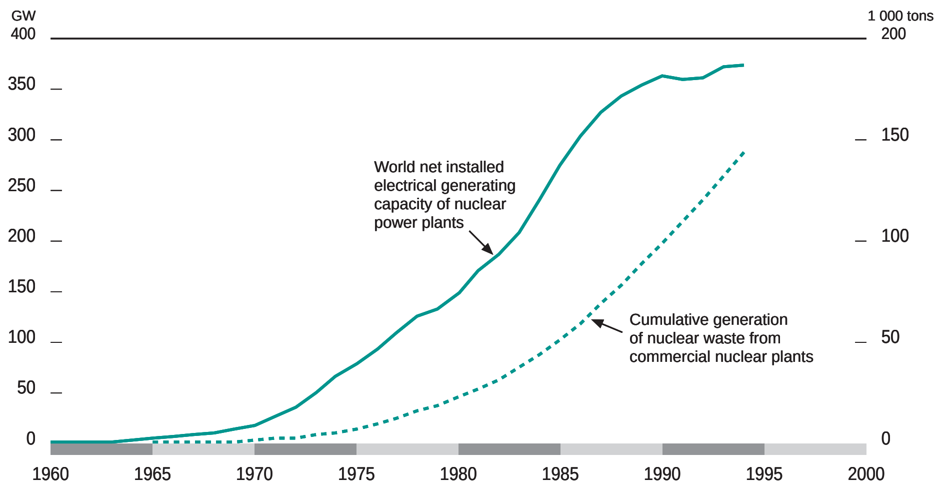

*Source:* "Structural Transformation Process Towards Sustainable Development in India and Switzerland". Infras, Zurich, May 1996.

per capita). On the other hand, industrialised countries may reduce their present energy consumption by a significant amount, *e.g.* at least 50 per cent. Risks are inherent in both: the former could demonstrate the limits of nature's adjustment capacity and the impossibility of quickly modifying the global energy system; the latter may lead to policy failures in the required transformation of the global energy system.

### *Radioactive waste*

Although experts continue to claim that radioactive waste disposal is technically feasible, real solutions are still pending. It may be true that this is primarily due to political and social obstacles. But the technical obstacles are no less daunting. Meanwhile, radioactive isotopes involved in the nuclear fuel cycle, especially plutonium, are accumulating and the volume of radioactive waste is growing (Figure 5). According to the Worldwatch Institute (Brown *et al.*, 1995), civilian nuclear reactors alone produced some 50 tons of plutonium in 1994, enough to build more than 6 000 atomic bombs. Clearly, the problem of controlling this material in the long run is extremely urgent, as it represents a growing threat to the principle of non-proliferation of nuclear weapons material.

Figure 5. **Installed power of nuclear power plants and their cumulative generation of radioactive waste**




*Source:* Brown *et al.*, 1995.

These five problems, all key issues, are strong reasons for concluding that the present energy system is not sustainable and that changing course towards sustainability is a crucial challenge of our times.

Yet it should also be noted that some of the problems above are currently less threatening than certain local problems related to energy consumption. Among those, air pollution (mainly caused by traffic) in the rapidly growing urban areas of the developing world is the most severe.

Surface mining, which now represents 27 per cent of coal mining activities, may exert significant stress on local ecosystems. Presently, about 300 square kilometres are used for coal mining every year. Areas that size take a period of twenty to thirty years to be recultivated.

Exploitation of hydropower may interfere locally with aquatic ecosystems as well as with, for example, drinking water supply and irrigation. With a typical water demand of 10 cubic metres per kilowatt-hour produced, the present global hydroelectric power production of 7 600 PJ per year involves 17 000 billion cubic metres of water each year.[6] This corresponds to 40 per cent of the global annual rainfall on land. It is estimated that presently, only 15 per cent of the total global capacity of hydropower has been developed and that yearly energy production could rise to

50 000 PJ. In this situation, a cubic metre of water falling on land would on average be used nearly three times for hydroelectric power production before it reached the sea or evaporated. The exploitation of hydropower would then reach global dimensions and lead, in combination with growing demand for irrigation, to a significant change of the present global hydrological regime.

The production of oil and gas creates further dangers to the environment. About 0.08 per cent of annual crude oil production is lost to the environment, mainly to water. This amounts to 3 million tons per year, equal to the total lost in all major tanker accidents to now. Losses linked to the production and distribution of natural gas are directly related to atmospheric greenhouse gases. They represent about 9 per cent of the methane that enters the atmosphere. This corresponds to nearly 2 per cent of the total anthropogenic greenhouse warming potential.

## 3. Towards a sustainable future: needs and limits

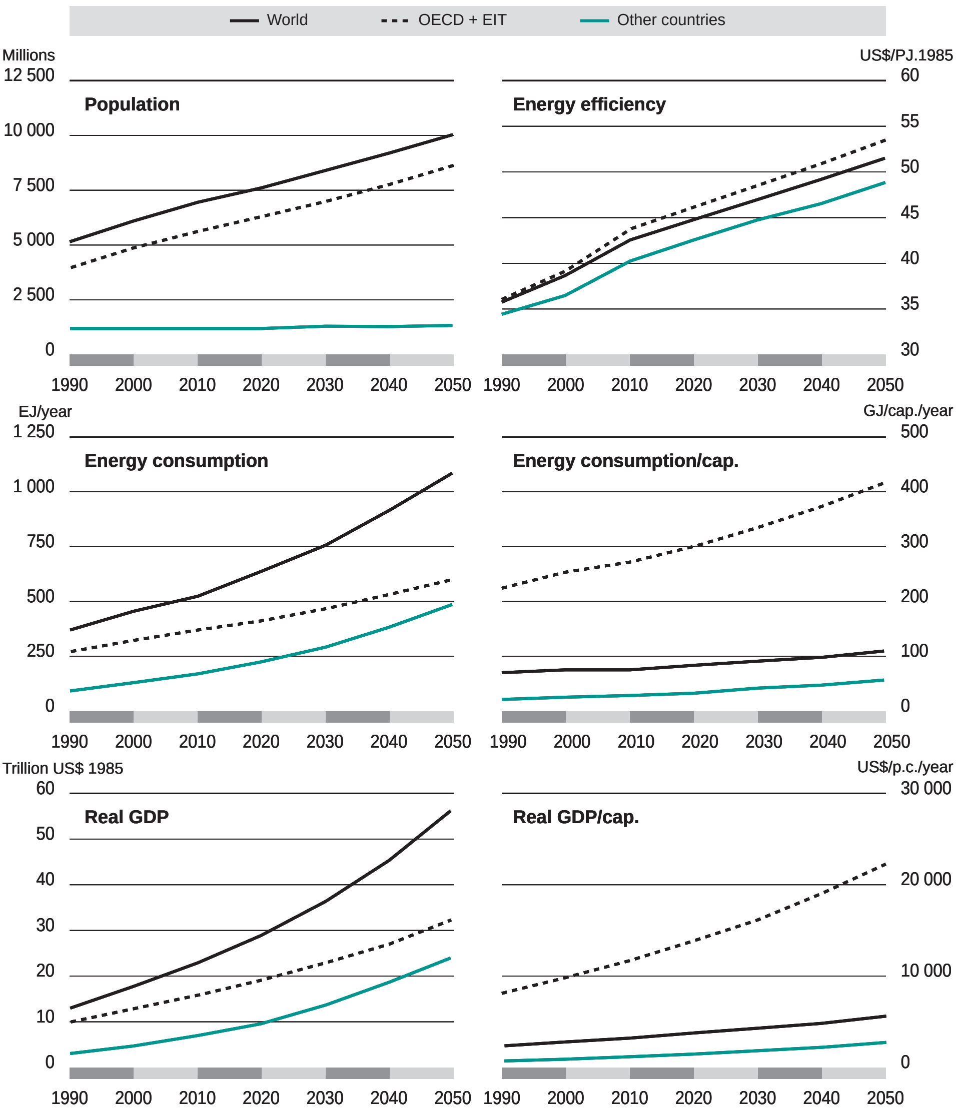
What then are the prospects for a transition towards a sustainable energy system? Figure 6 shows the development of key indicators from 1990 to 2050 as predicted by the OECD Green Model. According to the model, total energy demand will rise from its present value of about 300 EJ per year to more than 1 000 EJ per year. This development will be accompanied by a broadening of the already existing gap of per capita energy consumption between industrialised and developing countries. Per capita consumption in the latter would increase by 20 per cent to about 100 GJ per capita and year (about 3 000 watts per capita). In the former, it is expected to double, reaching a value of more than 400 GJ per capita and year (12 000 watts per capita), which exceeds today's value for the United States.

Clearly, any forecast of energy demand entails an implicit forecast of energy prices. It is just as easy to envisage a different future with much lower demand at much higher prices, and available technologies and consumption patterns may vary as well. In any case, it is necessary to take a closer look at the prospect of global energy use rising to 1 000 EJ per year by 2050.

Could such energy demand be met in a sustainable manner? Presently, more than 90 per cent of the energy supply is based on fossil fuel. In order to play a substantial future role at the predicted energy level of 1 000 EJ per year or more, any alternative energy resource must have a production potential of several hundred EJ per year – which is beyond that of energy sources such as wind, geothermal or noncommercial energy. At this scale, there are basically three options: fossil, nuclear and solar, or combinations of these. The use of biomass is included in the solar option. These three possible energy paths are analysed below with respect to both resource potential and the environmental impact they would have at this level of production.

Figure 6. **World indicators, 1990 to 2050**

Real GDP = Global gross domestic product based on price index of 1985. EIT = Economies in transition (former Soviet Union member states). 1 EJ = $10^{18}$ joules.

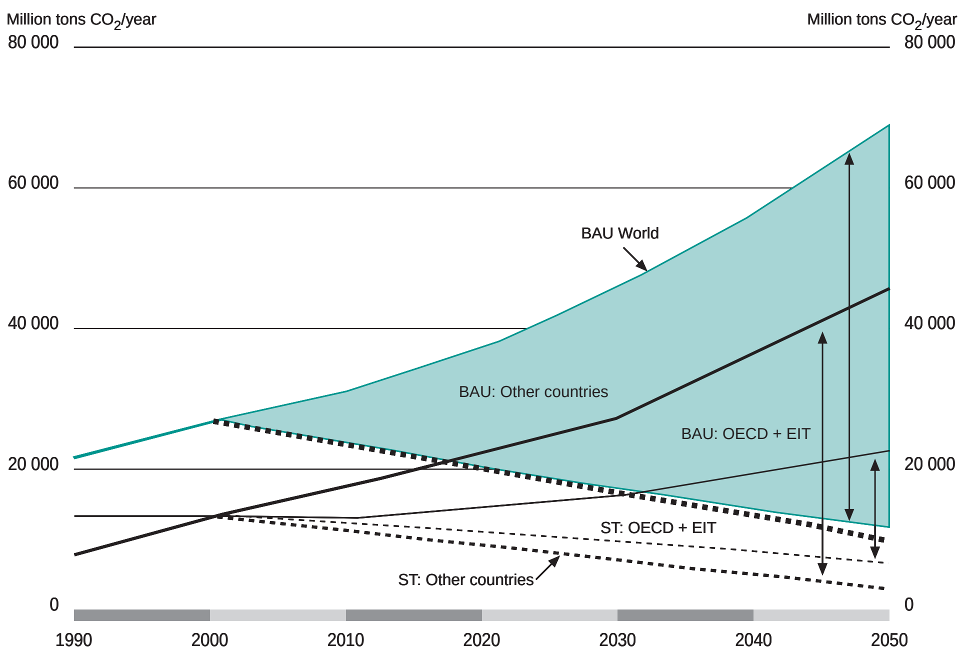



*Sources:* OECD (1995), *Global Warming: Economic Dimensions and Policy Responses*; and the International Energy Agency (1998), Energy Statistics, www.iea.org.

### *The fossil option*

According to the IPCC's report, sometime in the next century the ever-increasing emission of $CO_2$ (Figure 3) will have to level off and then to decrease to a rate well below the present figure of about 22 000 million tons per year. Opinions differ only on how soon such a decrease should begin and the level total emissions should eventually reach. Figure 7 shows the whole range of possibilities by comparing two extreme scenarios, a "business-as-usual world" (BAU) and a "sustainable target world". The former includes the commitments made by the industrialised countries at the Kyoto conference in 1997 with respect to the reduction of their atmospheric $CO_2$ input.

Figure 7. **$CO_2$ emissions**
Including Kyoto commitments




*Note:* Comparison of two extreme $CO_2$ emission scenarios, a modified Green (OECD) scenario (BAU = Business as usual) and a sustainable target scenario. The latter aims at a steady-state atmospheric $CO_2$ concentration of not more than 450 ppmv.
*Sources:* OECD (1995), *Global Warming: Economic Dimensions and Policy Responses*; the International Energy Agency (1998), Energy Statistics, www.iea.org; Infras.

The following conclusions can be drawn from this picture. The fossil option will continue to play an important role as a global energy resource for another few decades. However, if the aim set forth by the IPCC is to be taken seriously, then sometime between 2020 and 2050 the burning of fossil fuels will have to decrease to levels corresponding to half the present consumption rates, or less. If global energy consumption is indeed growing as predicted, other resources will have to provide the larger part of these needs beginning in about 2030.

Otherwise, due to limitations of oil and gas resources, the fossil path could only be pursued by falling back on coal. Since for a given quantity of coal energy consumption the production of $CO_2$ is twice as high as for gas and 50 per cent larger than for oil, continuation of the fossil option would eventually lead to an overproportional increase of $CO_2$ entering the atmosphere. In this context the crucial question arises whether solutions will be found that make use of coal without dumping the $CO_2$ that results into the atmosphere. There exist several ideas of how to tackle this problem from a technical point of view, but it remains to be seen whether these concepts are realistic when dealing with 20 000 million tons of $CO_2$ per year or more.

### *The nuclear option*

The boundary conditions for the nuclear option are summarised in Table 4. Optimistic analyses estimate an installed nuclear power capacity of 1 100 to 1 800 GWe[7] in the year 2050. This is three to five times more than today's capacity. Yet, according to Figure 6, total energy demand would grow by a factor of three.[8] Thus, during the next fifty years the relative share of nuclear energy would either remain constant or grow by less than 100 per cent. In any case, nuclear energy would not make a significant contribution to business-as-usual demand in 2050.

If nuclear power were to become a major component, *e.g.* by covering an annual energy demand of 300 EJ electric power (corresponding to an average power of 10 TW), then the number of nuclear power plants would need to increase

Table 4. **The nuclear option**

| | 1994 | 2050 |
|---|---|---|
| Number of power plants | 431 | 12 000[a] |
| Capacity installed | 350 $GW_e$ | 12 000 GWe[b] |
| Power produced | 270 $GW_e$ | 10 000 $GW_e$ |
| Capacity predicted | | 1 100 to 1 800 $GW_e$ |

*a)* To sustain a global park of 12 000 power plants with a life expectency of 40 years, 300 plants have to be replaced each year.
*b)* Corresponds to total energy consumption in 1995 (310 EJ = 310 × 1 $0^{18}$ Joules); $GW_e$ = $10^9$ Watt electric power.

30 times, leading to a total of 12 000 plants. With an estimated life expectancy of forty years for every plant, each year 300 plants would have to be replaced in order to keep production capacity constant. Known uranium reserves would then last only for about a decade unless the reactors presently employed are replaced by breeder reactors, thus increasing the energy potential of uranium by a factor of 50 to 60. Eventually the nuclear path would have to shift to fusion, although the probability is small that fusion could ever become available before 2025 to 2045. The production of radioactive waste, the availability of isotopes suitable to build nuclear bombs, and the likelihood of those accidents that occur with statistical regularity would all grow in proportion to the number of new plants. If these dangers were accepted as inherent in a desirable energy system, their consequences would make nuclear power much more expensive than energy from fossil fuels.

### *The solar option*

Solar energy in all its facets raises the greatest public expectations. It includes biofuel and its growth, the installation of solar cells for electricity production, and the construction of solar collectors for low-temperature thermal energy, *e.g.* for space heating. On a local basis and for individual countries, solar energy no doubt represents an extremely promising and sustainable method of energy production. However, this discussion has to do with producing 1 000 EJ of commercial energy per year, and at that scale things are not so simple.

The global solar energy fluxes are summarised in Table 5. The largest energy gains can be achieved with low-temperature (up to 50 °Celsius) solar collectors, which can be used to cover the energy needs for space heating and warm water production. This application has no negative environmental effects and may be important for the total energy mix of certain individual countries. However, on a global scale, low-temperature heat represents only a small fraction of the total energy use under consideration here.

A second possibility of solar energy exploitation is through harvesting biomass, either as so-called crop fuel or as wood. It is not possible, according to Table 5, to gain today's total energy demand from existing forest land. Alternatively, plantation of crop fuel would take up nearly half of today's crop land. Obviously, this is out of the question: given the ever-growing human population it would be disastrous if poorer countries were tempted to neglect the nutrition needs of their people in order to export crop fuel to satisfy the energy needs of the rich countries. Moreover, constraints of water availability will make the competition between crop fuel and agricultural food production cruel: food prices will rise drastically, and feeding the general population in many developing countries will be impossible.

Table 5. **Global solar energy flux and its potential use by man**

| | Per earth surface area (Watt per $m^2$) | Total ($10^{12}$ Watt) |
|---|---|---|
| Total solar radiation at earth surface | 240 | 122 000 |
| Global commercial energy consumption (1992: $310 \times 10^{18}$ J per year) | 0.02 | 10 |
| Human physiological energy demand (100 Watt per person) | | 0.6 |
| Biological gross primary production | | |
| Total (land + ocean) | 0.25 | 130 |
| Land | 0.44[a] | 65 |
| Solar energy production | | |
| Photovoltaic cells | 3 to 6[b] | |
| Low temperature solar heat collectors | 30 to 60 | |
| Biomass: Crop fuel | 1 to 2 | |
| Wood | 0.1 to 0.2 | |

To produce the total present energy demand ($10 \times 10^{12}$ Watt) the following areas are needed:

| | |
|---|---|
| By photovoltaic cells (at 5 Watt/$m^2$) | $2 \times 10^6$ $km^2$ |
| By crop fuel (1.5 Watt/$m^2$): | $6.7 \times 10^6$ $km^2$ (46% of crop land) |
| By wood (0.15 Watt/$m^2$): | $67 \times 10^6$ $km^2$ (160% of forest land). |

*a)* Related to land area without Antarctica ($130 \times 10^6$ $km^2$).
*b)* 1 $m^2$ of solar cells on the average produce 10 (mid latitudes) to 20 Watt (low latitudes). If combined into large solar energy plants, 1 $m^2$ of solar cells needs about 3 $m^2$ of space.

Photovoltaic production of electricity yields less energy per unit area than solar heat collectors, but it is more versatile. A total area of 2 million square kilometres could produce today's total commercial energy. There are no obvious reasons why, from a technological point of view, this should not be achievable within the next fifty years. However, electricity prices from solar cells are still about eight times higher than actual prices for electricity, and a switch to photovoltaic electricity production may involve a considerable increase in energy prices. At some stage, therefore, business-as-usual may lead to a choice between cheap energy from coal – with the ensuing climate change – and much more expensive energy from photovoltaics. Moreover, the dedication of 2 million square kilometres (the area of Mexico) to the production of energy and the necessary distribution and storage system would obviously be a problem in itself. The political and institutional difficulties in implementing such a system would no doubt be considerable.

To summarise, the solar option could only become a major supplier for business-as-usual energy demand for 2050 if huge photovoltaic power plants are built, *e.g.* in the desert areas of the low latitudes.

### *The basic dilemma*

It is not possible to assess environmental stress due to the production and use of energy without referring to the argument of absolute scale. Both from a local and global point of view, a much larger variety of energy resources may be involved if per capita energy demand does not grow beyond its present value of about 2 000 watts. Obviously, this would only be feasible if the present per capita energy consumption in the industrialised countries significantly decreases from the typical numbers of today (4 000 to 13 000 watts per person) in order to give leeway to those countries whose energy consumption is still below 1 000 watts per capita. The future energy system could then become a well-balanced mixture of fossil, hydro, solar and even nuclear contributions. In addition, smaller resources such as wind, tides, and geothermal energy could play a role. A healthy mixture avoids the concentration of environmental stress on just a few components of the global ecosystem. It also allows for tailor-made solutions, *e.g.* the production of low-temperature thermal energy by solar heat collectors and of electricity by photovoltaic cells, and thus increases the overall efficiency of the energy system. Finally, a diverse system is probably less vulnerable with respect to political and social stress on the local as well as global levels.

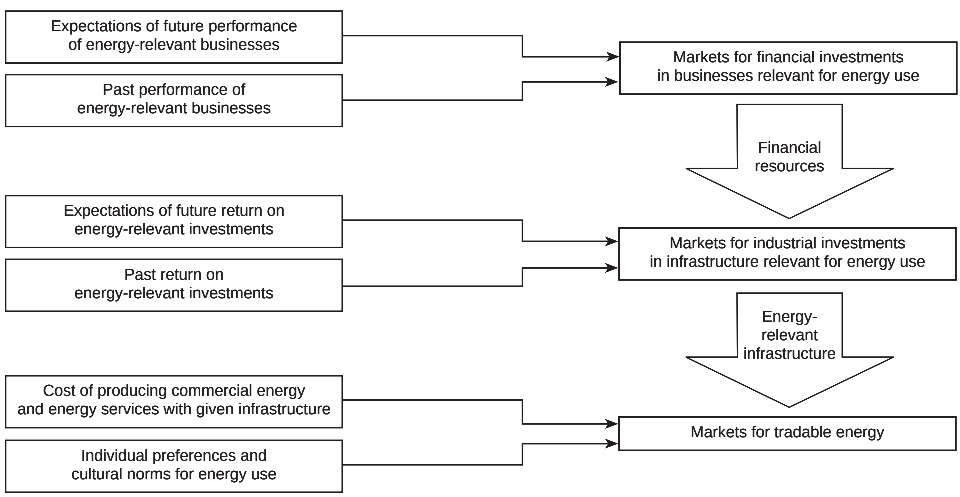
In contrast, if global energy demand, as predicted by most models, were to grow by a factor of three or more, the options would shrink to just three alternatives which all carry major disadvantages. The fossil option would eventually raise atmospheric $CO_2$ levels by a factor of three or more, and thus possibly trigger a series of global changes which, even if identified as dangerous, would then be impossible to turn around. The solar option, probably the least harmful of all, would be expensive and use a lot of land, while the nuclear option, whose technical feasibility remains to be proven, brings with it the need for extreme global political stability. Thus, it may well be that the real challenge of our generation is not to develop large new energy resources, but to find means to decouple the energy needs of the society from its wealth and standard of living (Jaeger *et al.*, 1997). Such an attempt would clearly mean a non-marginal transition – not just of the energy system, but of society as a whole.

## 4. The energy challenge

So far, it has been shown that current levels of energy use raise serious problems in a variety of domains, and that these problems are not simply due to the kind of energy used. If operated at a similar scale, conceivable alternatives raise similar problems. Therefore, gradual changes, *e.g.* improvements in the cleanness and efficiency of given energy production and utilisation methods, though important, are insufficient to reach a sustainable energy system within the next fifty years.

The problem, then, is how to trigger non-marginal changes in the global energy system. In order to design a solution, it is important to take a closer look at how decisions about global energy use are actually made in today's market economy. Figure 8 gives some indication.

Figure 8. **Decision-making about energy use**




*Source:* Author.

Individuals and households use energy to obtain services which fit their personal preferences, in turn often shaped by cultural norms. As an example, consider the role of meat in daily diets – a factor with considerable impact on agricultural energy use. Consumers' choices clearly depend on energy prices and household budgets, but they also depend on the infrastructure in place. (It is rather difficult to live in Los Angeles without using a car, for example.) The same holds for energy services used by firms: they, too, depend heavily on the existing infrastructure. This infrastructure, for its part, depends on past investments. Investment decisions, however, are driven to a very large extent by expectations. This holds both for the industrial investments which bring about roads, tunnels, skyscrapers, airports, etc., and for the financial investments made by individuals and institutional investors who decide which businesses they want to provide with money.

Such decisions are driven by expectations of future prices, not by future prices. There simply are no futures markets for power plants fifty years from now, or for roads, aeroplanes, dwellings, etc. In today's economy, long-term investment decisions are governed not by price mechanisms, but by expectations of how price mechanisms will work out. How, then, are these expectations formed? Financial as well as industrial investors have no choice but to make guesses based on their gut feelings combined with whatever information they may be able to gather from the rest of the world and from each other. One of the most important inputs in this process of expectation formation is provided by the scientific community. Nevertheless, what emerges from the process is by no means a scientific forecast, but rather a willingness to bet on certain developments.

Currently, investors' expectations about long-term energy development tend to focus on a business-as-usual perspective. There are hedging strategies, with some investments dedicated to preparing for alternative infrastructures, but the main bets are placed squarely on the existing infrastructure. This means that the dynamics of the global energy system are governed by a search for marginal improvements in the infrastructure already in place.

This situation raises difficult issues for policy-making. On the one hand, the absence of futures markets for energy infrastructure means that market mechanisms cannot take care of long-term energy perspectives. On the other hand, governments should not be expected to be able to develop more adequate expectations than private investors: they do not have access to better information, and they are as biased as any social actor by their own short-term interests. However, with regard to environmental issues, a series of scientific insights are available which may help to focus the process of expectation formation around long-term energy perspectives. One such insight has just been elaborated: it points to the importance of non-marginal changes in the future dynamics of the global energy infrastructure. Further insights are:

*a)* Levels of energy use in highly industrialised countries drive levels of global energy use via the global diffusion process of lifestyles and technologies.

*b)* Non-marginal changes can lead to a sustainable energy system within about five decades. Such a system is based on the decoupling of energy utilisation from economic growth and on increasing energy efficiency through its intelligent use – both end-use and at the level of infrastructure.

*c)* Policy measures to foster the transition towards a sustainable energy system should not be focused on the prices of final energy services, but on price signals for energy infrastructure and on improving the process of expectation formation around long-term energy prospects.

These are examined below.

### *Dynamics of energy efficiency in a globalised society*

To understand the dynamics of energy use at a global scale, it is essential to acknowledge the diffusion of technologies and lifestyles from industrialised into developing countries. This is a fundamental mechanism of today's world society. In a very general sense, three core values can be shown to have spread from industrialised into developing countries over several decades: economic well-being, formal education, and urbanisation. The mass media as well as personal contacts fostered by global mobility – ranging from tourism to refugee migration – have already had an irreversible impact in this regard. Attempts to attain these values in developing countries, however, differ markedly in their success. Urbanisation is progressing at breathtaking speed, formal education is spreading somewhat more slowly, and economic success is much harder to attain. For energy use, this means that energy-intensive lifestyles spread much more rapidly than the energy-efficient technologies to attain them. Moreover, the different speed of the three processes also means that life expectancy increases much earlier than birth rates start to decline, leading to massive (although hardly unlimited) global population growth.

The three global values mentioned above are not the only ones. Two more deserve special attention here. The first is human equality. In the past, empires based on very strong social inequality could last for millennia without ever being challenged in the name of human equality. Ancient China and Egypt provide some of the most instructive examples. Today, social inequality persists all over the world, but its legitimacy is much more fragile. In particular, the huge tension between the wealth enjoyed in some parts of the world and the extreme poverty prevailing in others is seen as unacceptable by most people everywhere. In practice, this leads to strenuous attempts by the majority of humankind to emulate consumption patterns, lifestyles and technologies displayed by the minority living in highly industrialised countries. This means that high rates of energy use in the most affluent parts of the world actually induce growing rates of energy use in the rest of the world.

Lastly, but certainly not least, a very recent global value merits special attention here: the value of being in touch with nature. Since the early 70s in highly industrialised countries there has been a remarkable trend of increasing population in peripheral areas where people can live among the green. The other side of the coin is an even stronger trend of decreasing population in large urban areas. But there is more to the phenomenon than that. At the same time, environmental concern is very much a reality for a large portion of the general population – a worldwide phenomenon – while so-called counter-urbanisation is restricted to highly industrialised countries.

Clearly, the value of being in touch with nature is an important driving force towards sustainable development. However, individual intentions are rarely linked with collective outcomes in a straightforward way. In particular, counter-urbanisation currently increases energy consumption rather than reducing it. This is due to the fact that until now the trend has increased travel distances between workplaces and dwellings, and further increases distances for leisure trips.

These global values shape individual preferences, consumption choices, workforce training, technological trajectories and institutional arrangements. With regard to energy consumption, two scenarios should be distinguished: business-as-usual, and sustainable development.

The difference between the two is not primarily one of demographic dynamics. Therefore, a single numerical example for global population can be used for the two. World population fifty years from now may well be about twice as large as today's figure; the total could be as high as 10 billion. Moreover, at a global scale a certain social stratification of this population seems inevitable. For the sake of simplicity, consider four social strata: a top layer of 1 billion, an upper middle class of 2 billion, a lower middle class of 4 billion, and a lower class of 3 billion. (The mechanism illustrated does not depend on these specific figures.)

In a business-as-usual scenario, the top layer of the global population must be expected to use energy at an even higher rate than North Americans do today – with an increase from about 10 kilowatts to perhaps 15. A crucial factor in this increase is likely to be additional air travel; another could well be the heating and cooling of larger dwellings, often placed in climatic zones which invite heavy cooling. As stated above, 1 billion people are estimated to be in that class. In a business-as-usual scenario, this fraction of the global population sets the trend which the rest of the world seeks to imitate. The global upper middle class may be quite successful at this, reaching the rate of energy use typical of western Europe today, *i.e.* about 5 kilowatts. In this example, that rate should be expected to hold for about 2 billion people. For the lower middle class of 4 billion people, the rate may become 3 kilowatts per capita, somewhat below the current rate for western Europe. The population share that uses energy at a very low rate, say about 1 kilowatt, is likely to decrease. Today, about one-third of global population, *i.e.* 2 billion, may use 1 kilowatt or less of commercial energy. Fifty years from now the fraction may be slightly smaller, with the absolute number reaching 3 billion. This leads to an average of $[1 \times 15 + 2 \times 7 + 4 \times 4 + 3 \times 1]/10$, or about 5 kilowatts per head.

The point of this numerical exercise is not to arrive at a precise number, but to illustrate the mechanism of diffusion from the global upper class through the middle classes and possibly even to the lowest class. In the current global society this mechanism applies to high energy use as a symbolic and technical support of wealth and power. In a scenario of sustainable development, by contrast, high energy use would be supplanted in that role by high energy efficiency. Simultaneously, the simple top-down and centre-periphery pattern of social diffusion would most likely give way to a more complex pattern, where the upper middle class sets the tunes which are gradually taken up by society as a whole. In the last decades, similar diffusion patterns have already been observed in many realms, including music, consumer durables and leisure activities.

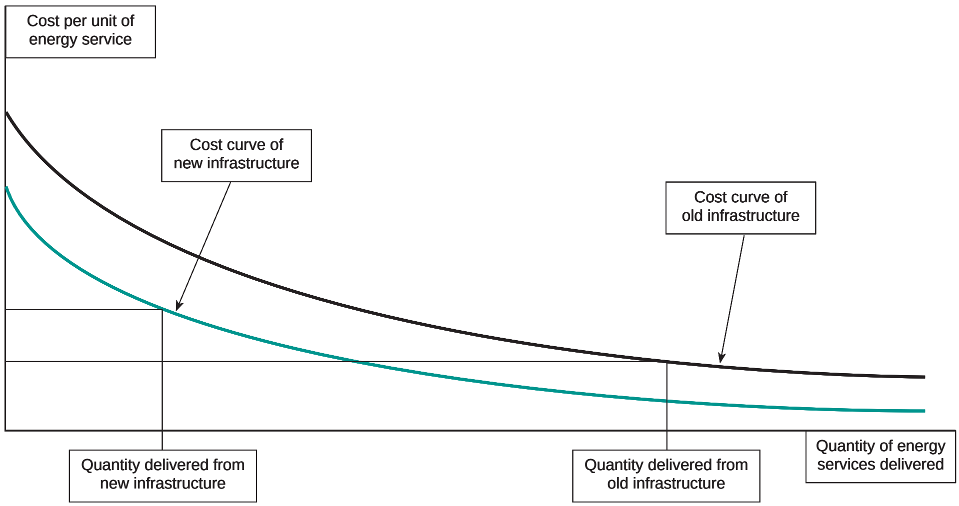
With regard to energy use, a sustainability scenario could be based on the upper middle class reaching a high level of energy efficiency, leading in turn to a low level of energy use at a rate of 2 kilowatts per head. This possibility is examined in greater detail below. For the moment, an upper class is added which increases energy efficiency too, albeit more slowly, with the result that a rate of 5 kilowatts is reached. The global lower middle class must be expected to increase its energy use but less than in the business-as-usual scenario, reaching 3 rather than 2 kilowatts. This leads to an average of [1 × 5 + 2 2 × 2 + 4 × 3 + 3 × 1]/10, or 2.4 kilowatts per head.

Both diffusion processes are perfectly compatible with a market economy driven by profit-seeking firms and investors, as well as by consumers striving to fulfil their needs and wishes as best they can. The processes differ in two respects. The first has to do with the way consumers deal with their needs and develop their wishes. From diets to entertainment, people look at each other when they make their choices. This leads to bandwagon effects in consumption patterns – and, depending on the initial trigger, these may induce very different rates of energy use. Second, firms and investors also look at each other when they form the expectations without which they could not make long-term investments. Once again there are bandwagon effects, this time in technological trajectories, and once again these may lead to very different rates of energy use.

### *Non-marginal changes in the energy system*

If global energy use is governed by a diffusion process from the global upper or upper middle class to the rest of the world, it is obviously crucial to understand the possible dynamics of the initial triggers. It is often assumed without further scrutiny that the market selects the unique best choice out of the set of available technologies. Figure 8, however, should make us wary of such assumptions. They require financial and industrial investors to form their expectations about the distant future in such a way as to identify and implement not only the most efficient ways of using energy in the framework of a historically given infrastructure, but also the most efficient infrastructure itself. This is not so easy, as Figure 9 shows. The existing infrastructure engenders huge fixed costs. After all, it consists of highways,

Figure 9. **Lock-in effect for infrastructure**




*Source:* Author.

airports, dwellings, skyscrapers, pipelines, car factories, etc., all of which today represent the sunk costs of investments made in the past. This infrastructure is currently operated at a large scale; therefore, the fixed costs can be distributed over huge quantities of energy services, making these cheap. If an alternative infrastructure has to be started, it will need to compete with the existing infrastructure by operating at much lower levels. This means, however, that the old infrastructure will prevail. Increasing returns due to high fixed costs lead to a lock-in effect for infrastructure.

Figure 9 illustrates the difference between marginal and non-marginal changes of the energy system. With a given infrastructure, one can move along a smooth curve and fine-tune small changes so as to maximise efficiency under the constraints set by that infrastructure. And clearly efficiency does not relate simply to quantities of energy delivered to end-users, but also to the energy services which these end-users get for their money. There can be no doubt that considerable increases in energy savings are still possible along these lines. Over the past decades, cars, aeroplanes, heating and cooling systems, computers, etc. all have become more energy-efficient, a development that may well continue into the next decades.

However, this way of increasing energy efficiency is always counteracted by tendencies to use more energy still. As aeroplanes get more energy-efficient, people fly more frequently; as heating and cooling get more energy-efficient, people live in larger houses; as computers get more energy-efficient, more computers are put into use, etc. On balance, marginal changes in today's energy system are likely to slow the growth of per capita energy use somewhat, but without even keeping it constant.

A transition towards a sustainable energy system, then, can be achieved only by non-marginal changes, *i.e.*, by switches in the relevant infrastructure. Given the analysis of the preceding sections, it is not difficult to see that the crucial changes are the ones not in energy production, but in energy use. And here the most important infrastructure is by far the urban fabric. Three elements can be singled out: thermal insulation, commuting distances, and leisure opportunities.

As for thermal insulation, it is technically feasible to design buildings that use very small amounts of commercial energy for heating and cooling while providing higher comfort than existing ones. In particular, humidity regulation is very poor in most urban buildings worldwide. Besides the lack of comfort, this is one of the most serious causes of respiratory diseases. As the relevant technologies can become competitive only at large scales of production, a classical lock-in problem arises.

Commuting distances involve very different issues. The spatial patterns of urban regions have evolved from two sources: the classical form of a city, with a centre surrounded by increasingly peripheral areas; and the industrial era, which made it an obvious choice to separate areas of manufacturing plants from areas of dwellings. The location of workplaces is now heavily dependent on information technologies. At the same time, today's service-based economy is highly sensitive to personal contact networks. This has led to polycentric urban regions with car traffic, the basic medium of transport, bridging increasingly long distances in all directions. It would be perfectly possible, however, to develop a working culture where people co-operating in a business meet physically only during part of their worktime. The other part may be spent working either at home or in satellite offices within walking distance from home. There are many ways in which such arrangements could be realised – but again, they are competitive only if implemented at large scales.

Leisure opportunities are important determinants for energy use. There is no reason why urban regions in a service economy should not provide highly attractive leisure opportunities in the immediate neighbourhoods of where people live, which would lead to greatly reduced energy use. Clearly, there is a human need for mobility which in today's global society will not be satisfied by any leisure activities close to home. But again, there is no need to stick to the present infrastructure, which offers long-distance car trips and air travel as the main ways to satisfy this need for mobility. Future levels of energy use will depend critically on the question of whether a different infrastructure for leisure activities will emerge.

Non-marginal changes in urban infrastructure, however, take time to be realised. In the industrialised countries, which will probably be the ones setting trends for future energy use, the large urban infrastructures in place are renewed at a rate of about 2 per cent annually. In five decades, then, urban infrastructure can be completely overhauled simply by taking advantage of the regular renewal rate. The challenge is not how to build a new city on a green site, but how to reshape existing cities by redirecting the infrastructure renewal process.

If this is done, it will be accompanied by far-reaching transformation of energy production and processing. As explained in Section 3, a sustainable energy system will operate at a rate of energy use sufficiently low to offer scope for a wide mix of primary energies. This corresponds to the management strategy of robust action: reach short-term goals while keeping your long-term options open. With regard to the energy system, this may be specified as the principle of constant time of safe practice. Starting now to reshape the renewal process of cities in industrial countries would provide opportunities to transform the global energy system in such a way as to maintain a reasonable level of flexibility – a flexibility that would be lost by a business-as-usual trajectory of the energy system currently in place.

***Policy measures***

What policy measures can be recommended to deal with the energy challenge of the next century? The standard answer is to increase energy prices via taxation.

This is usually justified by claiming that energy use engenders negative external effects that cannot be handled by the market without policy measures aiming to internalise these effects. In particular, climate change will hurt large regions of the world, and the price of fossil fuels needs to be increased so as to take these effects into account. This can be achieved by a tax or by an arrangement of tradable permits. As for taxation, it should be kept in mind that oil is already one of the most heavily taxed products in the world and provides a major source of revenue for many governments. When considering a tax to internalise negative environmental effects, then, the question arises whether such internalisation actually requires even higher levels of taxation. With regard to tradable permits, the question is how much fossil use should be permitted. Both questions are hard to answer, but informed guesses are possible while the rest would have to be fixed by a process of trial and error.

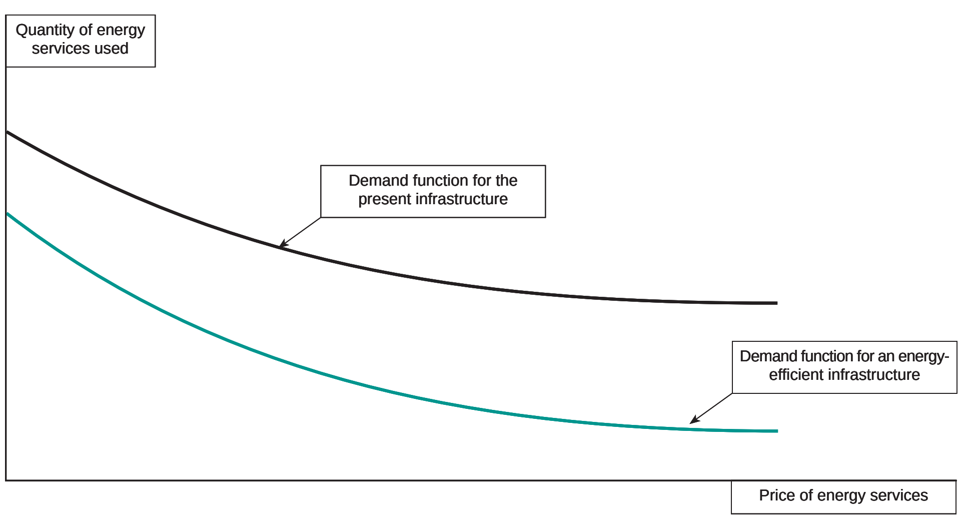
An analogous reasoning holds for nuclear power generation. Here, too, there are external effects in the form of risks and damages borne by people who are not and – as in the case of severe accidents and of future generations – often cannot be fairly compensated for them. Again, a case may be made for internalising these effects either via taxation or via tradable permits, and again the question arises as to the appropriate level for either of these instruments. Incidentally, even those opting for totally phasing out nuclear power generation may wish to consider such instruments to implement the phase-out.

In practice, this overall view of energy markets has put various proposals for energy taxation on the policy agenda, where they are the subject of continuous negotiations and lobbying. They are unlikely, however, to be implemented on a large scale unless negative external effects of energy use become much more salient than they are today.

If one trusts the capability of the global energy system to adjust smoothly to large and irreversible price increases, then energy policy loses much of its alleged importance and can become a matter of routine management, to be operated with limited resources at a rather low profile. This, however, is a big "if".

Figure 10 explains why. Adjustments of energy use to changing energy prices are governed by demand elasticities. Under present circumstances, a 10 per cent increase in energy prices must be expected to induce a reduction of energy use by much less than 10 per cent. This is due to a large extent to the existing infrastructure.

Figure 10. **Demand elasticities for different infrastructures**




*Source:* Author.

One energy price, then, can induce two very different levels of energy use, depending on the infrastructure in place. What is usually considered the demand elasticity of energy use is always relative to a given infrastructure. And an analogous reasoning holds for elasticities of supply for various sorts of commercial energy.

Obviously, energy prices are the right controls to influence energy use with a given infrastructure. But are they the right controls to influence energy-relevant infrastructure? The argument illustrated by Figure 8 and 9 calls for caution here.

Cities and transport systems are in place, and they engender needs for heating and mobility that are hard to vary in the short run. Given the present infrastructure, there are no doubt considerable opportunities to reduce energy use, and price increases will make it advantageous for millions of firms and households to seize these opportunities. After all, this is what happened after the two oil shocks of the 70s and 80s. However, the basic infrastructure was maintained: more than ever cities are built so as to rely on car traffic, more than ever houses are built so as to rely on energy-intensive heating and cooling, etc. A different, more energy-efficient infrastructure is perfectly conceivable, but the price increases of the two oil shocks were reversed without triggering a switch to such an infrastructure.

The dynamics of energy-relevant infrastructure are governed first of all by the expectations which financial and industrial investors hold about the future.[9] Their expectations do not depend primarily on past energy prices. These prices are common knowledge among investors, and they are obviously taken into account; but what makes the crucial difference in this realm are expectations about the future dynamics of technologies, lifestyles and natural resources. Moreover, decisions about infrastructure investment are strongly influenced by prices of crucial items of that infrastructure. Prices for highways, residential dwellings, cars, etc. are not very sensitive to energy prices, as they depend on many other factors as well.

For the energy price to be the best control to influence the global energy system, the world economy would need to involve perfect information about all relevant facts, instantaneous adjustment of all markets to that information, futures markets for most goods over the next two or three centuries, and technologies which never display fixed costs and increasing returns. It is well known that this a fairyland fantasy, not the market economy in which humankind is actually living.

Given the role of lock-in effects and of subjective expectations in the long-term dynamics of the global energy infrastructure, an energy policy geared to taxation may mean that major business opportunities are missed.[10] To seize these opportunities, however, non-marginal changes in the global energy infrastructure need to be taken into consideration. Sometimes, this line of argument has been used to justify state intervention in infrastructure planning. Making that kind of leap, however, is a risky move.

As discussed in relation to Figure 8, there is no reason to suppose that governments have more adequate expectations of the constraints and opportunities faced by future energy systems than private investors. Given the role of increasing returns and technological progress in this field, governments cannot even know whether higher energy efficiency will lead to higher or lower energy prices in the long run. After all, it is perfectly possible that a more energy-efficient infrastructure will be set up for reasons which have nothing to do with energy prices, and that as a result demand for commercial energy will fall. Computers have displaced typewriters without any increase in typewriter prices. This is not to say that energy taxation should be ruled out as a measure of energy policy, but it is to say emphatically that such taxation should not be considered as the main instrument of energy policy.

If taxation is to be considered, it might be equally and sometimes more advantageous to apply it to the hardware on which energy use depends. An instructive example is the tool of "feebates" on cars. A small fee of, say, \$20 on each sale of a standard car could be collected to finance a rebate on each sale of, say, a city car using less than 3 litres per 100 km. At the beginning, such a rebate could more or less offset the whole price of the city car. As the new product penetrates the market, the rebate would lose its weight until it would simply disappear once the old product has been displaced. The point of such an instrument is that it is tailored to fit technologies marked by increasing returns and lock-in effects – precisely the situation encountered in energy systems.

As with taxation, tradable permits may be much more effective when they are applied not to energy as such but to the energy-relevant infrastructure. This is of major importance with regard to urban development. The traditional view of urban planning is long dead: there simply is no authority that could design and control in a centralised fashion the urban regions of our times. Only if mechanisms can be utilised for the purposes of sustainable development, rather than put in the strait-jackets of political planning, can a transformation of urban infrastructures be realised. This will mean unpacking present property rights of land into different components and allowing market trade for those components. For example, there may be tradable permits to use land for manufacturing purposes, for traffic, for private use, and so on. By giving these permits time limits and setting their quantities in accordance with goals of local sustainability, urban renewal can be fostered by market mechanisms within the perspective of sustainable development.

These examples should suffice to show that the transition to a sustainable energy system is a complex process that will require a complex of measures, not a single catch-all trick. Some of the most efficient measures may be "soft" policies, geared to the opportunities of a knowledge society rather than to the mechanism of the late industrial society. In particular, governments can and should make a deliberate effort to improve the process of expectation formation by private investors as well as by society at large wherever this is possible. It is vital to identify the business opportunities associated with a transformation of urban infrastructures as well as changes in the systems of energy production and use in the decades to come, and to bring entrepreneurial talent to the task of realising these opportunities.

One crucial measure for this purpose is the design and implementation of ongoing dialogues between financial and industrial investors with an interest in energy-relevant infrastructure, representatives of government agencies with related interests, and scientists capable of assessing options in this area. Experience shows that long-term personal links between highly qualified individuals are required for sound processes of expectation formation. Obviously, a body such as the OECD can play a significant role in this strategic policy area.

# Notes

1. Writing this paper would have been impossible without professional assistance from INFRAS Consulting, Zurich. The chapter draws on research conducted in the projects ULYSSES and VISIONS, financed by the fourth framework programme of the European Union; in the project CLEAR, financed by the Swiss Priority Programme "Environment"; and in the project "The 2000 Watt Society" conducted within the framework of the Swiss Federal Institute of Technology. The authors are grateful to Hadi Dowlatabadi, Ottmar Edenhofer, Larry Goulder, Jean-Charles Hourcade, Bernd Kasemir, Claudia Pahl and Christoph Schlumpf for stimulating discussions. The usual disclaimers apply.
2. In this chapter, energy is measured in joules and energy flows in watts. One watt is an energy flow of one joule per second; a kWh (kilowatt-hour) is the same amount of energy as 3.6 million joules. A year comprises about 31.5 million seconds, or about 8.8 thousand hours. Therefore, an energy flow of 1 kW corresponds to a yearly energy use of about 8 800 kWh or 31.5 billion joules. With regard to abbreviations: 1 PJ = 1 petajoule = $10^{15}$ joules, and 1 EJ = $10^{18}$ joules = 1 billion billion joules.
3. Conventionally, the primary energy of nuclear power is calculated as the total thermal energy produced by the fission of nuclear fuel. Only about one-third is converted into electricity. In contrast, hydropower plants convert 80 to 90 per cent of the water's potential energy into electricity. Thus, although both hydropower and nuclear power each contribute about 2.5 per cent to global primary energy consumption, the contribution of hydropower to electricity production is nearly three times larger than that from nuclear power. An analogous argument holds for solar energy.
4. For an attempt to assess long-term prospects of global change with explicit consideration of the problem of uncertainty, see Rotmans and de Vries, 1997. See also Hammond, 1998.
5. A wait-and-see approach is certainly inferior to policies that are attentive to inertia and viability in a dynamic setting. See Hourcade and Chapuis, 1995.
6. The same water may be used several times, as when several hydroelectric plants are installed along the same river.
7. GWe = Gigawatt electric power = $10^9$ watts electric power.
8. One may argue that the nuclear option could increase energy efficiency because of a favourable energy mix between electricity and thermal energy. It is hard to see, however, how this factor could reach the order of magnitude required to make nuclear energy a significant fraction of total energy supply a few decades from now.
9. Edenhofer and Jaeger (forthcoming) offer an evolutionary model for the dynamics of energy use.
10. For an attempt to identify mechanisms of opinion formation of financial operators in this field see Toth *et al.*, 1998.

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# Energy Demand Patterns Towards 2050

*by*

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## 1. Introduction

People use energy through the application of technology to satisfy their needs for comfort, light, mobility, processed products, etc. This relationship between energy use and basic human needs makes energy a fundamental input to almost all aspects of human economic activity – as a necessary component of all household heating and cooling equipment, as a fuel for the world's fleet of cars, trucks, ships and aeroplanes, as the enabler of industrial processes. Historically, the link between energy and economic growth has manifested itself in the so-called Iron Law of energy demand: 1 per cent economic growth leads to roughly 1 per cent energy demand growth.

However, all forms of energy transformation and use entail some form of pollution and/or environmental degradation. Unfortunately, barring a utopian future, improving the environment will generally mean economic costs; a trade-off between material wealth and environmental wealth will have to be made. There are five basic options available to those who wish to improve the environment:

- *Fuel-switching* – Switch towards a more environmentally friendly but more costly fuel. Renewables are at present an extremely interesting option, although there are some environmental challenges associated with these as well.
- *Cleaner fuels* – Improve the environmental characteristics of the fuel, as the refining industry has done for a long time, through the phase-out of lead, reduction in sulphur content, reduction of aromatics, etc.
- *Emissions reductions* – Make some additional investments in order to clean up the emissions generated, as has been done in the power generation market

through flue gas desulphurisation and in the auto industry through the introduction of the catalytic converter.

– *Energy efficiency improvements* – Make capital investments that increase the efficiency of energy production or use, for instance through better insulation of buildings, heat pumps, etc.

– *Comfort sacrifices* – Make comfort sacrifices, for instance by accepting reduced mobility, reduced heating and cooling, or slightly lower automotive performance in exchange for improved energy efficiency.

All these options entail costs – sometimes significant costs – but in a world that is steadily getting wealthier, the demand for environmental quality will undoubtedly grow. Furthermore, technological development and innovations will bring the cost of improving the environment down, thereby changing our common future outlook. However, we must never forget that there is no silver bullet that will solve all our problems. Technology will certainly be of the utmost importance in addressing the challenges that stand before us, but unless the human factor is taken into account, we will fail dismally in our quest for a better future.

This chapter briefly reviews and discusses how social and technological change-enablers might break the trends and challenge the business-as-usual scenarios of energy demand patterns beyond 2020. It will not present full-blown scenarios with quantifications, or a consistent set of underlying assumptions and relationships; it will, rather, focus on the potential trend-breakers and speculate around their specific contribution. The discussion begins by introducing the widely different developments and challenges of the rich and poor countries of the world, and examines how consumer lifestyles and purchasing patterns are affecting the economic structure of society and hence energy demand. It continues with a look at how energy efficiency might be improved through the application of advanced energy-efficient technologies, and concludes with the wild card of the future: how developments in IT technologies might transform the way we work and live.

## 2. Consumer demand: saturation or surge?

From an economic perspective, there are wide variations between the situations in different parts of the world. For the roughly 1 billion people living in the high-income countries in the OECD, the average per capita GDP is around $25 000,[1] while for the more than 3 billion people living in the low-income countries the average is less than $2 500.[2]

In terms of energy consumption the picture is similar, although the vast amount of energy used in China has led to a higher share of energy consumption going to the low-income countries. The population in the OECD countries consumes 4.5 tonnes of oil equivalent (toe) on a per capita basis, and the population of the rest of the world (ROW) consumes around 0.8 toe each, once more highlighting the tremendous imbalance. Of the energy consumed in the world, around 39 per cent is used in the industrial sector, 27 per cent in the transport sector, 19 per cent in the residential sector and 8 per cent in the commercial sector, the remainder relating to agricultural and non-specified energy use.[3]

The majority of the population in the rich OECD countries have long satisfied the basic need for food and shelter, and are now focusing an increasing share of their attention on lifestyle-related desires. The desire for mobility has been growing for some time, but parallel to this development there is a growing focus on the health effects of pollution and the possibility of disruptive changes in the global climate due to anthropogenic greenhouse gas emissions. It is impossible to predict how the balance between these concerns is going to develop in the long-term future. It will, *inter alia,* depend on the public perception of the importance of climate change, the lifestyle sacrifices that will have to be made in order to improve the situation, and the technological options available.

The picture in the less affluent countries of the developing world, on the other hand, is radically different. In these countries there is still an urgent need to satisfy the most basic requirements of food and shelter, clean water and primary health services. Improving the local environment plays an important role in improving the quality of life of the population, a point that will receive growing emphasis. The negative effects of energy use and energy transformation can, however, be reduced through relatively simple improvements in fuel quality and fuel-switching. It will not be necessary to mandate radical changes in the way energy is used, as substantial changes will occur anyway as a natural consequence of the modernisation of the economy and the turnover of capital stock.

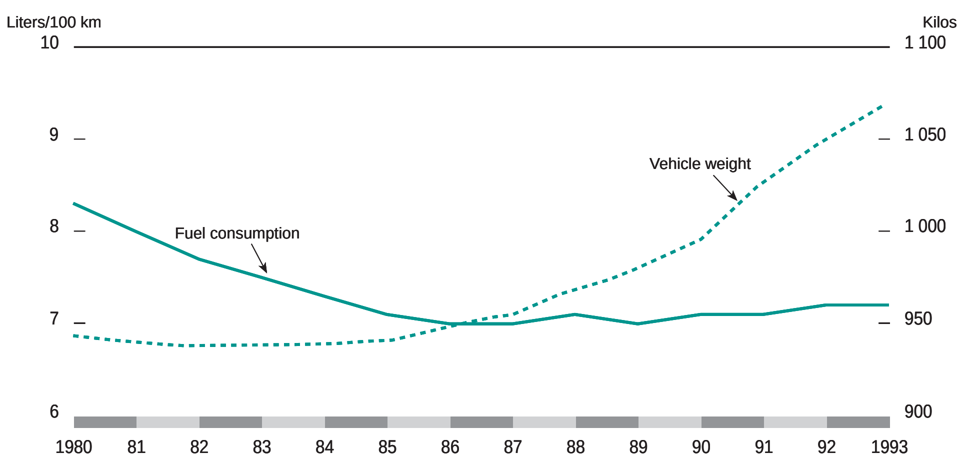
The challenges, constraints, opportunities and trade-offs in these two parts of the world are thus radically different, which will lead to radically different developments. The rest of this section on demand is accordingly divided into two, reviewing the OECD countries before continuing with the rest of the world.

### *OECD countries – environmental challenges and saturation?*

In the OECD countries, the potential for saturation has long been discussed: there is a limit to how many cars or the level of heating and cooling one person "needs". Initially, the consensus was that the saturation level for car ownership would be reached once every household had a car. When this level was breached, without any signs of a slowdown in the growth rate, it was assumed that growth would surely slow down and even decline once there was a car for every licensed driver. However, the economic relationship between income growth and demand has led to an ever-increasing car density in all countries, albeit at a slightly reduced rate of growth.

In principle this continuously rising car stock should not have a significant impact on energy demand – a person can only drive one car at a time – but even this saturation element has failed to materialise: gasoline demand in the United States continues rising almost in line with economic growth. Although technological improvements have increased the fuel efficiency of any given automobile type, consumer tastes have increasingly been moving towards larger cars, with air conditioning and other energy-consuming accessories. Figure 1 shows how this trend towards ever-larger cars has cancelled the effect of technological improvements on energy efficiency in seven western European countries over the past decade.

Figure 1. **New car fuel efficiency and vehicle weight, average for seven European countries,[1] 1980-93**




1. Germany, Austria, Belgium, France, Italy, United Kingdom, Sweden.
*Source:* CCFA; La voiture moyenne en Europe, 1994.

In 1994, on-road fuel efficiency was between 8 and 11 litres per 100 km in western Europe and between 13 and 14 litres per 100 km in the United States. In the latter country, the shift towards compact vehicles that was observed following the first oil crisis was reversed, and consumer interest in larger, more luxurious models was renewed. The decline in the market share for small cars from 33 per cent in 1992 to 26 per cent in 1997 is one indication of this trend. A further contributing factor to decreasing energy efficiency in the United States has been the increasing use of "light trucks", including small pickups and minibuses, for personal transport purposes. Light trucks accounted for 32 per cent of the personal private vehicle market in that country in 1990, and their fuel consumption per km is about 36 per cent higher than that of cars. However, this trend towards ever-larger automobiles is not immutable. Most basic mobility purposes are served just as well by a compact car as by a pickup – or even better. History is full of examples of rapid movements in consumer lifestyles and tastes, and the transport sector is no exception. Increasing environmental concerns are one factor that could lead to a much larger focus on energy-efficient transportation modes and technologies, the potential of which will be discussed in more detail in the following sections.

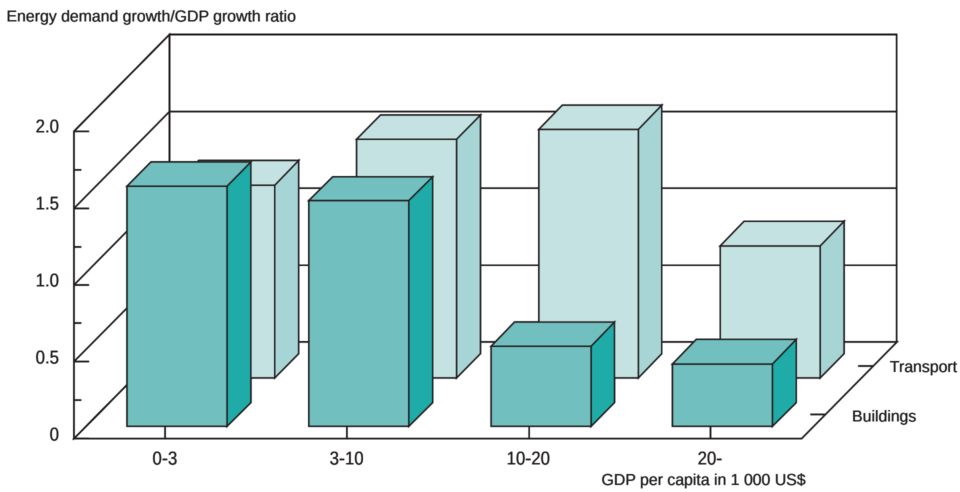
***Non-OECD countries – economic development and surge?***

In the developing countries the situation is totally different. In populous countries such as India and China, income levels have only recently reached levels where it becomes affordable for an ordinary citizen to buy a private car. At the same time these countries have been experiencing a long period of booming economic growth, leading to a dramatic surge in energy demand. Many of the once dynamic countries of Asia are currently having serious economic problems, with declining levels of economic activity leading to a reduction in the levels of energy demand. Although it will take time for these economies to emerge from the crisis, it is the authors' firm belief that these countries have the potential for resuming the dynamic growth seen previously, albeit at slightly reduced rates.

With the expected economic growth leading to further improvements in the living conditions of the populations in these countries, a significant share of the increased income is likely to be used to purchase energy-consuming equipment. Figure 2 indicates the effect of this development on the energy market during the past decade. The figure shows the ratio between energy demand growth and economic growth for 71 non-OPEC, non-CPE countries[4] in the 1986-94 period, which was characterised by approximately the same energy price conditions expected over next couple of decades.

The figure clearly shows the importance of energy for residential purposes in the low- and middle-income countries. Once income levels breach the $10 000/capita level, the basic needs of heat, light and cooking have mostly been met, and the relationship between economic growth and energy demand weakens significantly in this energy-consuming segment. In the transport sector on the other hand, the demand for energy starts taking off at the level of income that makes the purchase of private automobiles affordable, roughly $3 000/capita. As incomes rise into the middle- and high-income levels, the relationship strengthens further as consumption patterns start switching towards long-range air travel and other

Figure 2. **Energy – economy relationship, 1986-94**




*Note:* GDP weighted averages of 71 countries.
*Sources:* WEFA; IEA.

leisure activities. It is important to note that for the low-income categories, the demand for energy grows faster than economic growth in both segments, indicating that under a continuation of current trends the energy demand growth in these countries has only just begun.

Another important characteristic of energy demand in developing countries is the high share of noncommercial fuels such as biomass, dung, etc. In Asia around 80 per cent of residential energy demand and around 35 per cent of total energy demand is covered by this energy source, compared to around 7 and 3 per cent respectively in the OECD countries.[5] This high share of noncommercial fuels is largely a consequence of the high rural population in these countries.[6] As the economic transition from traditional rural societies to more industrialised and service-centred urban societies proceeds, the logistical challenges connected with the use of these traditional fuels will lead to a reduction in their share of the total energy mix. The growth in demand for commercial fuels will, in other words, most likely be even higher than the already rapid growth in demand for energy in general.

There will thus be radical differences between developments in the maturing OECD countries and in the emerging non-OECD countries. The surge in demand from the emerging economies will in all likelihood far outpace any tendencies towards saturation in the maturing economies. However this is not inevitable, and in the following section we will examine some of the available technological options that might break the trend.

## 3. Trend-breakers

### *Energy-efficient technologies*

As mentioned in the introduction, consumer energy needs are related to the need for heat, light and power. Today this end-use energy is mainly based on the transformation of chemical energy to electrical and mechanical energy through combustion of different types of fossil fuels and biomass. The amount of final energy that is delivered by a given amount of primary energy is governed by the laws of thermodynamics. Increasing the amount of final energy will require either increasing the temperature of combustion, or some means of capturing the waste heat. In a modern gas-fired power plant, around 60 per cent of the primary energy is transformed into electricity through the use of gas turbines in combination with steam turbines powered by the waste heat from the gas turbine. This technological option is not directly available for coal-fired plants, thereby limiting the electrical efficiency to around 40 per cent. A modern automobile is able to achieve transformation efficiencies slightly above 30 per cent under optimal operating conditions. In addition to the energy lost during the transformation from chemical energy to electrical/mechanical energy, a substantial amount of energy loss occurs in buildings, through ventilation losses and thermal diffusion through the walls, roofs and windows. The following section analyses the technological options for improving the transformation efficiency and reducing heat loss in buildings.

#### *Fuel-efficient vehicles*[7]

In addition to the presence of energy-consuming add-on features, such as air conditioning, the factors determining the fuel efficiency of road vehicles are mainly engine design, vehicle weight and aerodynamics. The energy losses of a representative travel cycle are due to heavy thermodynamic losses in the engine, energy absorbed by auxiliary items, and overcoming internal friction in the power-train. The power that does reach the end of the power-train must overcome external forces such as aerodynamic drag, which increases exponentially with car speed.

Most of the time, cars are running at light engine loads, while car engines are typically designed for the heaviest load they are likely to encounter. As an example of this, the maximum power for most new passenger cars exceeds 130 horsepower, whereas the average power actually used is only 8 horsepower. At this power level, engine efficiency is only about 17 per cent, a figure that could be increased substantially if the engines are designed more in line with the average power than the maximum power. Technologies with the potential to raise engine load efficiencies could be enumerated as follows (Mendler, 1992):

– *Hybrid power-trains* combining combustion engine and electric motor(s), which allows engine load and rpm optimisation, as in the new Toyota Prius, which according to Toyota allows a doubling of energy efficiency.

– *Advanced transmissions* and continuous variable transmission, which allow the engine to run within a more optimal load and rpm range, improving the energy efficiency by some 10 per cent.

– *Variable valve control*, which reduces throttling losses. Eliminating the throttling process altogether would improve overall fuel economy by up to 20 per cent.

In addition to the gains that can be achieved by optimising engine load, significant efficiency improvements can be made through the following factors:

– *Lean burn engines*. Today's spark-ignition engines with catalytic converters must burn stoichiometric fuel-air mixture. Engine efficiency can be improved by raising the air content and allowing a higher compression ratio, yielding a fuel economy gain of some 10 per cent, as in the new Mitsubishi GDI.

– *Engine preheating or engine heat retention*. Much driving takes place with a cold engine. For the average passenger car trip length in the United States of 7.8 miles, engine warm-up reduces fuel consumption by 12 per cent on 21 °C days and by 16 per cent on 7 °C days.

– *Variable compression ratio* can theoretically increase the thermodynamic efficiency of the engine by 30 per cent, but this remains speculation.

In addition to the fuel efficiency gains through improved engine design, significant improvements have been achieved in recent years as a result of better aerodynamics. During the past twenty-five years the average drag coefficient for the average European car has been reduced from 0.45 to 0.30, improving the energy efficiency by some 30 per cent. Furthermore, the increasing use of lightweight metal alloys and composites – along with better design of the mechanical parts – has provided a continuous improvement in energy efficiency.

It must be expected that all of these options will be pursued, leading to a steady improvement in energy efficiency in the longer-term future. However, moving beyond the next fifteen years, the options for improving the efficiency of the internal combustion engine will be ever-harder to attain, and radical redesign of the power-train will be needed.

Fuel cells are arguably the most interesting of these new options for improving efficiency; there has been a significant acceleration in the development of this technology over the past five years. Hydrogen is the fuel best suited for fuel cells, but methanol, naphtha, gasoline and natural gas are also suitable after reforming onboard the vehicle. Daimler Benz, through their in-house technology development and their alliance with Ballard, is among the leaders in this area. Currently, the Proton Exchange Membrane (PEM) fuel cell offers the most attractive future prospects, through its combination of simple design, high power/weight ratio and low working temperature. It is expected that the efficiency of a PEM fuel cell running on hydrogen will be approximately 40 per cent.[8]

*Fuel-efficient aircraft*

During the era of high oil prices in the 1980s, energy costs accounted for almost a third of operational expenditures for civil aircraft. Although this share has been falling in line with falling oil prices, improving fuel efficiency has continued to be a primary objective of aircraft operators and manufacturers. Developments in the United States can serve as an illustration of improvement over the past decades. Since 1970, US passenger traffic has more than tripled, increasing at an annual rate of 6.6 per cent. During the same period, energy use increased only 43 per cent, an average annual increase of just above 2 per cent; thus, the number of passenger miles per gallon of fuel has doubled. Three developments have been driving this impressive improvement in energy efficiency:

– more fuel-efficient engines;
– larger aircraft with a higher number of seats;
– higher passenger load factors following the deregulation of the airline industry.

As the air fleet is gradually renewed, newer fuel-efficient engines and airframes replace older, less efficient equipment.

Since its introduction in commercial aircraft in the 1960s, the jet engine has evolved from turbojet to turbofan to high bypass (HB) turbofan, with ever-increasing efficiency. Current HB turbofan engines are 40 per cent more fuel-efficient than the original turbojet engines. The use of improved materials capable of supporting higher combustion temperatures has also contributed (Greene, 1990).

For subsonic aircraft, a major propulsion efficiency advance can be realised with the Ultra High Bypass (UHB)[9] concept. Ducted UHB turbofans have been shown to yield efficiency improvements of 10-20 per cent. Unducted or propfan engines using advanced propeller designs have achieved 20-30 per cent efficiency increase over current turbofan engines. Advanced designs using twin counter-rotating propellers have overcome the previous speed limitation of turboprops, enabling aircraft to achieve Mach 0.8-0.9 with propfans. However, these advanced designs presently have a high cost disadvantage, and will require significantly higher fuel prices to become economical for the airline companies. Beyond 2010, improvements in fuel efficiency would have to come from the introduction of new engine concepts. One example might be the use of lightweight heat exchangers to provide charge cooling and recuperate exhaust heat from the engine. If such technologies could be applied in aviation, they could in theory yield 20-25 per cent energy savings. All in all, a further increase in engine efficiency of 40 per cent is theoretically possible without any loss in performance.

Further improvement in the technical efficiency of aircraft can be achieved through the use of lighter-weight material. Modern lightweight composite materials have the potential to reduce airframe weight by 30 per cent, with equal or better structural strength. To illustrate the need for this weight reduction, it takes around 1 tonne of jet fuel to lift a 100 tonne aircraft to a cruising altitude of 10 000 m, assuming a conversion efficiency of 25 per cent. In a typical round trip, this represents an important share of total energy consumption.

Finally, the current unproductive stacking of aircraft waiting to land represents energy waste that could be reduced through improved tools for the planning and control of airport operations. Studies indicate that automated tools for improved flight planning, airport operations planning and air traffic control could reduce fuel consumption by 6 per cent, while the further increase in aircraft size could lead to another substantial reduction in energy use (Greene, 1990).

However, for all the developments towards more efficient technologies, the air transport system of the future will not necessarily be more energy-efficient than the current system. A revival of supersonic air transport could very well reverse the current trend. Although the current fleet of ageing, inefficient Concorde aircraft are by no means indicative of the energy efficiency of a future fleet of supersonic aircraft, they will certainly be significantly less efficient than subsonic aircraft. Some market projections anticipate a fleet of some 300-1 200 commercial supersonic jets in service in the next 10-30 years (Archer, 1993). In this context it is important to remember that almost every transport innovation in the history of mankind has been less energy-efficient and more time-efficient than the technology it replaced.

*Energy-efficient buildings*

Unlike people, a building is doomed to stay outside in all kinds of weather. Creating an acceptable indoor climate regardless of weather conditions, at an acceptable investment and operating cost, is thus an increasingly important task for architects and heating ventilation and air conditioning (HVAC) engineers. Furthermore, the dramatic increase in the number of computers and other electronic equipment has presented the HVAC engineers with the new challenge of exporting the heat generated by this equipment.[10]

The energy used to heat or cool buildings is the direct consequence of energy fluxes between the building and the outside. These fluxes can be divided into three categories, all of which need to be addressed in order to improve the energy efficiency of buildings.

– solar radiation producing a heat flux into the building;

– transmission losses of energy through walls, roofs and windows;

– ventilation losses in the used air outlet and energy use for ventilation fans, etc.

*Solar radiation* – One important way of influencing the heat flux into the building is through the development of "intelligent" windows, with coating able to obstruct or let solar radiation energy pass through, depending on the conditions indoors. Such windows would not only reduce the heating energy necessary, since they allow a heat flux into the building under cold conditions; they would also reduce the need for cooling, since most of the heat influx into the building enters through the glass surfaces at an intensity of approximately 1kW/$m^2$.

*Transmission losses* through walls, roofs and windows are proportional to the temperature difference between the indoor and outdoor climate. As with the incoming solar energy flux, improving the windows is the most attractive way of reducing the energy need of buildings.[11] For windows, development of transparent insulation materials between window panes may replace today's air-filled or gas-filled window systems used in combination with reflective glass surfaces. In this way, transmission losses may be reduced to the same low amount as for the walls. Wall and roof losses are reduced by inserting an insulation layer, thereby increasing their thickness. This increases the cost while reducing the useable floor area. For new buildings, there is thus a balance between investment in wall insulation and energy cost.

*Ventilation losses* are related to the release of heated air, but also to the energy needed to run the ventilation fans. Heat exchangers to transfer energy content in the exhaust air to the inlet air are a well known and mature technology that would lead to a substantial efficiency improvement through more widespread use. Furthermore, the energy consumed by the current large ventilation fans may be greatly reduced by more use of natural wind and buoyancy forces to power the ventilation system. Such a solution would provide the additional bonus of a significant reduction in noise levels.

• Decentralised power production

Small combined heat and power (CHP) units, producing electricity at the point of consumption and using low-quality waste to heat water for residential and commercial purposes, are likely to play an important role in future energy supply to buildings. These units would be designed according to the heat demand of the building and integrated with the electricity grid, for balancing of the electricity need. A number of different engine technologies are currently under consideration for these systems:

– conventional engines running on diesel, natural gas or renewable fuels;

– small gas turbines running on natural gas or gas oil;

– Stirling engines running on a wide range of fuel sources;

– fuel cells running on natural gas or even hydrogen in a longer-term perspective.

• Heat pumps

Heat pumps represent the technology with, arguably, the greatest potential for increasing the efficiency of energy use in buildings. This technology converts otherwise unusable energy from external heat sources, for instance sea water and aquifers, into useable heating energy for buildings through the use of a refrigerant.[12] In heat pumps, low-temperature energy is transmitted to the refrigerant by vaporising it in a heat exchanger at the low pressure level. The vapour is then compressed to a pressure corresponding to a higher condensation temperature level, where the energy absorbed in the refrigerant is released by condensation. The only input energy needed to power the heat pump is the mechanical energy for the compressor, usually produced by electric motors. The efficiency of a heat pump or coefficient of performance (COP) is influenced by the temperature difference between the source medium and the recipient. Typical COPs range between around 3 for domestic users and 25 for large-scale industrial plants. Through the use of heat pumps the low-temperature process industry cooling water, commonly having a temperature of 10-20°C, can be utilised to heat residential areas, commercial centres, etc. At this temperature level water can be transported in pipes over large distances with very limited heat loss to heat pumps installed in homes, office buildings, hospitals, indoor swimming pools, etc., where the temperature level is raised to the desired level.

Norway represents a good example of a heat market in which pumps offer the possibility of a significant reduction in the use of energy in buildings. At present around 60 per cent of the total energy consumption in Norwegian buildings, or 30 TWh, is used for heating. Even in a country with as low electricity prices as Norway, it has been estimated that there is a potential for economical energy production from heat pumps of 25 TWh/yr at a rate of return of 7 per cent. This would yield a net energy saving of 17 TWh/yr.[13] The Statoil R&D centre in Trondheim is an example of an office site where a heat pump taking energy from sea water has been successfully installed, presently supplying around 70 per cent of the total heat need.

To sum up, technological developments in the transport sector, *e.g.* efficient hybrid power-trains and fuel cells, are likely to more than double the energy efficiency of cars, without any loss of performance, within the next couple of decades. In aircraft a similar efficiency improvement is likely to come through continued incremental improvements of engine technologies, lower-weight materials, and larger aircraft. The widespread use of solutions integrating low-temperature district heating based on waste heat from power plants etc., and local heat pumps and CHP units – along with intelligent building systems optimising the flux of solar energy into the building – will also lead to a significant reduction in energy requirements.

### *The changing economic structure*

As man's ability to innovate and improve productivity proceeds, societies are transformed. One such transformation was the shift from agricultural to industrial societies, as productivity-enhancing innovations in agriculture led to a surplus of labour that could be used in the emergent industrial sectors. We have seen the transformation from the industrial to the service society, and we are now seeing the transformation from the service society to the digital society, where there is no longer a need for physical contact in order to perform a transaction. Since one unit of value creation in the industrial sector consumes roughly 10 times as much energy as one unit of value creation in the service sector,[14] the latter's growth in importance will influence future patterns of societal energy use. As the development towards a dematerialised economy proceeds, we will see a trend towards ever-lower energy requirements per unit of GDP.

Furthermore, the transition towards the digital economy, where advances in telecommunications and computing are converging in the form of the Internet, is opening new opportunities for digital commerce and electronic distribution. Soon, virtually all information technology investment will be part of interlinked communications systems, whether internal to a business, between businesses, between individuals and businesses, or among individuals. In the United States, 25 per cent of economic growth and 8 per cent of economic activity are now being created in the PC sector, with software firms representing a substantial share of this figure.

There is no reason for this production to be distributed through the traditional physical distribution channels; electronic commerce can perform the task with greater efficiency through high-speed communication links. Digital commerce can take several different forms:

– Electronic commerce between businesses, where companies use the Internet to lower purchasing costs, reduce inventories and cycle times, provide more efficient and effective customer service, lower sales and marketing costs, and realise new sales opportunities.

– Digital delivery of goods and services to the end consumer: software programmes, newspapers, airline tickets and music CDs no longer need to be packaged and delivered to stores or news kiosks for subsequent further distribution to the home. They can be delivered electronically over the Internet.

– Interactive retail ordering of tangible goods: increasingly stressful working practices have shifted more focus to leisure time, spurring the growth of catalogue shopping during the 1980s and 90s, a service now being transferred to the Internet.

Although the trend towards digital commerce is still at a very early stage of development, the worldwide electronic commerce market, as the sum of the above three categories, is projected to rise from around $6 billion in 1996 to $150 billion in 2000.[15] US interactive retail sales are projected to rise rapidly to $56 billion in 2000, after which the growth rate levels off slightly, leading to a sales level of $115 billion in 2005.[16] In the United States, around 25 per cent of private transport is related to shopping purposes. With a large-scale introduction of electronic retailing, the need for physically going to the shop will be significantly reduced, with a consequent reduction in transport volumes. Furthermore, the need to distribute the goods to the shops will be eliminated, leading to an even larger reduction in freight volumes.

On the other hand, it must not be forgotten that the highly energy-intensive tourist industry is one of the fastest-growing industries globally, with the emergence of long distance air travel one of the important energy market developments since the 1970s. In the period since 1970, air transport volumes have consistently grown around twice as fast as the economy as a whole. In Norway, the share of transport- and travel-related consumer expenditures has increased from 7 per cent in 1958 to 20 per cent in 1994.[17]

### *Information and communication technologies as enablers of telework*

The sections above discussed how information and communication technologies (ICT) can make cars, aircraft and buildings more efficient with regard to fuel consumption, and how the digital revolution might transform the economic structure of societies, significantly reducing the need for physical transportation. The chapter's focus now shifts to how ICT might enable new working and trading practices – in some cases eliminating the need for physical transport. A crucial question in this context is of course the human factor: will the worker/consumer exploit the full potential to use ICT instead of physical transport, or will lifestyles and working practices remain unchanged?

*IT and telecommunications – technological position and development*

Basic technological development within IT and telecommunications has been advancing at a seemingly unstoppable pace. A couple of examples can illustrate this. The power of microchips has for a long while doubled every eighteen months. From 1985 onward we have seen a doubling of capacity in storage devices (disks) every year. These technical improvements have been followed by corresponding cost reductions. Although there are physical limits to growth governing how far these developments can proceed, the state of current research indicates that these limits will not be met within the next ten years.

In its early stages, telecommunication amounted to voice transfer. This is no longer the case. Currently, the global share of voice transfer has fallen to 50 per cent, not because of a drop in oral communication but because of the dramatic rise of data traffic following the cost reductions achieved in the telecommunications sector. This remarkable shift has been enabled by an even faster rate of cost reduction than in the computer industry. The expected continued fall in telecommunications costs will allow the amount of data traffic to continue growing at breakneck speed; if current trends hold, the share of data transfer is expected to reach 90 per cent by 2003. We are on a fast track development towards a world where physical distance loses its importance. As the technology improves further, the addition of visual capability, *i.e.* online full-motion video and graphics, to already widespread telecommunications technology could dramatically transform the way we work and live.[18]

The combination of reduced telecommunications costs and the mass marketing of personal computers opened the door to innovative new products and services, the dimensions of which were impossible to foresee. The Internet is a prime example of this; after twenty-five years of nondescript existence, the simple user interface of the Internet browser suddenly created a mass market of 100 million users within five years of its launch. To put this growth in perspective, it took the telephone industry forty years to reach 10 million users.

The transformation to a telecommunications society will not be without challenges, however. The rapid increase in demand for more telecommunication capacity is likely to create significant bottlenecks, the removal of which will require enormous investments. In order to expand capacity rapidly and efficiently, a set of standardized, robust and secure infrastructure services, *inter alia* in the areas of payment and intellectual rights management, will need to be established. Furthermore, this technology could increase the gap between developing and industrialised countries, through the changes it will introduce into the structure of the global economy. There is a possibility that the developing countries could be unable to progress beyond low-wage labour-intensive industries, while the industrialised countries focus on high-wage, knowledge-intensive sectors. Although this is a possible development, the rapid expansion of an internationally competitive software industry in countries such as India indicates that this danger is overstated. We must also remember that one of the main effects of ICT is the reduction and in some cases elimination of the localisational disadvantages of the emerging economies.

*Production of goods and services*

Another of the effects of the ICT revolution has been a substantial improvement in knowledge management and co-ordination systems. This development, in combination with the increasing knowledge component of goods and services, has opened the door to increasingly flexible and small-scale production systems. At the same time, intense competitive pressures arising from the ongoing liberalisation and globalisation processes are relentlessly driving forward new organisational structures, in the eternal search for efficiency. For instance, the new IT-enabled ways of co-ordinating activities have opened up for flatter and more decentralised organisational structures, wherein a large number of teams and assets are reporting directly to central management. The traditional functional specialisation is being reversed: each of the small asset teams performs many of the separate tasks that used to be divided among separate departments. Furthermore, the new ICT innovations permit an increasing degree of integration and experience transfer between design, engineering and manufacturing, without the necessity of locating these departments together. In addition, the simultaneous reduction in set-up and retooling costs is permitting production in smaller batch sizes, shorter production cycles and shorter delivery lags, effectively eliminating many of the economies of scale in a series of manufacturing industries.

All of these parallel developments will allow a greater degree of decentralisation of the production processes, thereby enabling the workplace to be located in or near residential areas. On the other hand, it must be emphasized that decentralisation will increase the need for intra-firm transport volumes of both freight and personnel, in many cases transported in small batches and numbers, thereby in effect reducing the energy efficiency of the transport system.

*Telework*[19]

One important aspect of ICT development is the way in which it opens up increased possibilities for telework, as a substitute for physical transport. This is by no means a new concept; the term was first coined in the 1970s, when authors like Alvin Toffler (1970, 1980) wrote enthusiastically about the neighbourhood "electronic cottage" as the workplace of the future. Optimistic forecasts of telecommuting's potential have been made ever since, but it is only in recent years that advances in telecommunications have reduced cost and technology barriers sufficiently to open up the potential for a more widespread use of teleworking practices. The term telework encompasses three different approaches to changed working patterns:

- day extenders, who typically work from home on an ad hoc basis in the evenings and during weekends;
- telecommuters, who typically telecommute part of the week;
- virtual office workers, who work from home or "on the road" and only turn up at the office for the occasional meeting.

These three approaches have similarities, but are not the same. The basis for the distinction lies in the difference between the elements constituting the core of the employee's professional life. Generally, a day extender and telecommuter have their core professional life "in the office", whereas virtual office workers can have their core professional life anywhere. Since the day extender physically commutes every day, the use of telecommunication is not a substitute for physical transport, but rather a complement. Telecommuting and virtual office working can, on the other hand, be regarded as a substitute for physical transportation.

All available studies point at productivity gains as an important benefit of teleworking. For example, the National Academy of Science conducted a test in the United States in 1985, which showed that telecommuting raised productivity by 15 to 25 per cent.[20] It also increasingly helps employees and employers cope with unexpected events that keep workers from reaching the office, from foul weather to natural disasters. In this respect it is interesting to note that average productivity after the California earthquake in 1994 increased by 12 per cent, when people were unable to go to work. Already in 1994, the total number of US employees that telecommute, formally and informally, full- or part-time, was estimated by various studies to be somewhere between 4 and almost 9 million,[21] or 3-7 per cent of the total workforce.

Although the speed of development of teleworking practices is most rapid in the United States, the trend is not limited to that country. A study by the Gartner Group shows an optimistic scenario, with the number of persons engaged in teleworking practices growing from 15 million worldwide in 1996 to 105 million in 2002.[22] This growth is unevenly distributed across the world, with the number of teleworkers in the United States increasing from the current 4-9 million to 65 million in 2002 – implying that almost 50 per cent of the workforce could be active in some form of teleworking by that time. In Europe the number of teleworkers is set to increase from 4 million to 30 million, while the number in the ROW is likely to rise from 1 million today to 10 million within this five-year period.

To illustrate how the development of teleworking practices might influence transportation patterns and energy demand, a Norwegian report[23] has evaluated how it might reduce the need for car travel. Since teleworking has the potential to act both as a substitute for and as a complement to car travel, a scenario was developed around each of these possibilities. In the scenario where teleworking is a supplement for physical travel, little is done to stimulate the development of telework, and only 10 per cent of the population is assumed to work at home for more than one day a week. In the scenario where teleworking is a substitute for physical travel, companies and public authorities at all levels co-operate to put in place more explicit, co-ordinated policies to encourage and stimulate teleworking. In this scenario, 20 per cent of the working population will be working at home one day a week or more. These scenarios, along with available demographic knowledge, are used as a basis for calculating the implications for car-based commuting in the main urban regions of Oslo and Bergen. The analysis demonstrates that teleworking has the potential to reduce travel and travel-based pollution in these regions. Although the impact on car use is limited to between 3 and 6 per cent, the impact on energy use will be much higher through the effect on traffic flows and the wasteful use of energy in rush hour traffic.

Although all technological barriers to the increased penetration of telework practices are expected to be overcome within a twenty-year time frame, most surveys and analyses indicate that substantial social, organisational and political issues need to be sorted out in order to pave the way for more widespread teleworking. For the individual teleworker, greater personal flexibility is frequently quoted as the most positive effect.[24] On the other hand, the teleworker's limited direct contact with management can often lead to a fear of losing out on promotion opportunities. Reduced interaction with colleagues and the lack of separation between work and leisure space are frequently referred to as negative social aspects of teleworking. Results from Statoil's employee survey indicate that the negative effects on career opportunities are exaggerated; the vast majority of respondents indicated no change or an improved relationship with management following the introduction of home offices.[25]

Seen from a traditional management angle, the prime inhibitor to telework seems to be the fear of reduced supervisory control of employees. This is, however, a common problem in today's organisations with cross-functional teams, and not specifically related to teleworking. Furthermore it is likely that developments in many aspects of organisational life will give rise to more objective work-related performance criteria that are applied to teleworkers and non-teleworkers alike, reducing the barrier even further.

Due to the significant advantages to both employers and employees, telework will mature and become an integral part of normal business in the OECD countries by 2010. Businesses will then have to rethink old concepts of office buildings and where to locate them. This might have an important impact on the future development of urban areas. Even if there are some factors that increase transport volumes as a consequence of teleworking practices, some decrease in

## The Statoil homeworking experience

### Background

Statoil views the continuation of the trend towards the knowledge society as a predetermined element in our business environment. As a consequence, an increased focus on technology and knowledge is seen as the main vehicle for gaining competitive advantage. This vision led to the launch, one year ago, of the IT Step, an education programme and major initiative to increase employees' knowledge of ICT and develop their ability to use that technology to their personal and professional advantage in the future. The IT Step initiative is fully financed by Statoil and includes the distribution of a state-of-the-art multimedia home PC with printer and free Internet connection. The employees are committed to taking a computer-based training programme in their spare time, focusing on generic PC skills, use of the Internet and other aspects of the information society, and Statoil's history and business environment. The computer is intended to be available to the employee's family as well as the employees themselves. The programme was presented as an offer to all 14 000 workers employed by Statoil at that time; more than 90 per cent have joined. So far the programme has been a great success, illustrated by an all-time high score in Statoil's annual survey of employee satisfaction and work conditions. It is also worth mentioning that after one year, more than 75 per cent of the participants state that they prefer this form of technology-assisted learning as opposed to traditional classroom teaching. An additional benefit from the IT Step is the wide outside attention and pioneer company image it has given Statoil.

### Telework experiences

Statoil is also very interested in exploring the potential advantages of telework, and has just finished a first formal project. With the IT Step infrastructure in place, it was easy to expand the home PC software to a home office work station for those involved in the project. The results from this pilot phase show that nearly 40 per cent had reduced their car usage, but that as many as 55 per cent said it had made no difference.[26] As regards changes in the use of public transport, more than 80 per cent said it had not influenced their behaviour. It is important to emphasize that this change in transport behaviour has happened in a context where most people have less than 30 minutes' travel time to the place of work. This is illustrated by the fact that a significant part of the reduced car usage stemmed from reduction in evening work at the workplace, and in visits to the workplace at the end of a long day of travel.

energy consumption for commuting purposes is likely as a result of the same trend. In the medium term it is not unrealistic to assume that the average worker will telecommute one day per week within the next year. Since transport for commuting purposes represents around 25 per cent of total private transport activities, this will lead to a 5 per cent reduction in transport volumes, all else being equal.

## *More efficient distribution systems*

As mentioned earlier, we are seeing a rapid increase in digital delivery of goods and services over the Internet, which will significantly reduce the need for physical transportation. In this section we will see how more efficient distribution systems might influence transportation patterns.

In this context there are two main challenges. In the distribution system itself there are the huge bottlenecks and congestion problems that are caused by poor traffic flows – a problem that could be significantly reduced through the introduction of intelligent vehicle/highway systems, IVHS. This is an important development for all users of transport infrastructure, for the individual industrial plant or commercial site. However, the main factor of concern is the huge amount of working capital tied up in inventories that are just waiting to be used. Over the past twenty-five years companies have increasingly turned to just-in-time (JIT) delivery as an important vehicle for achieving the reduction in working capital. One of the side-effects of this trend is that the inventory is moved onto the roads in smaller batches that are delivered more frequently, leading to a dramatic increase in transport activity.

### *Intelligent vehicle/highway systems*

At present substantial amounts of energy and time are wasted due to congestion and poor traffic flow. For instance, increased congestion on French roads during the period 1973-88 led to a 20 per cent increase in transport sector energy consumption (Hourcade, 1993). The solution of building more roads to solve congestion problems has been tried throughout the history of travel, so far with limited success. IVHS represent another, promising approach to improving traffic flow, through the incorporation of automated traffic management and systems for monitoring physical infrastructure, traveller information systems, automated vehicle control and systems for commercial vehicle operations.[27] The cost of deployment of a country-wide IVHS in the United States is estimated[28] to be around $40 billion over the next 20 years, in addition to a cost of $170 billion related to the installation of necessary equipment in the cars and trucks that are going to use the roads. Highway inefficiency costs of around $300 billion p.a.[29] could be cut by as much as 25 per cent with IVHS. Efficient, large-scale deployment of IVHS will require agreement on a set of common standards and co-operation at the international level, in order to ensure compatibility. It must also be remembered that efficient implementation of IVHS will require a significant transfer of control from the driver to the car and infrastructure system. The psychological challenges of this transfer should not be underestimated, although tests carried out by Volvo in Sweden indicate that drivers generally respond positively to yielding a moderate amount of control to the vehicle, and so in effect offering active help in following the speed limits.

IVHS can be introduced gradually in increasingly “intelligent” vehicles, a development already seen today through the introduction of local area network technology linking the myriad of processors already present in cars. Equally noteworthy are the first prototypes of passenger cars with anti-collision radar, allowing smaller distances between cars and larger capacity on the roads. As these prototype models are tested in the real world, the ongoing ICT revolution will bring down the cost of the technology, thereby allowing the current state-of-the-art technologies to find their way into mainstream car models within a very short time span.

*Just-in-time techniques*

JIT production is based on a complex logistics system with the overarching goal of reducing the amount of capital tied up in the company through the minimisation of inventory levels. One of the effects of JIT is that it moves the storage facility from the factory or warehouse onto the roads, thereby increasing the number of vehicles and adding to congestion problems – an effect further exacerbated by efforts to minimise batch sizes, leading to more frequent and smaller deliveries. Implementation of JIT techniques also leads to increased vulnerability to disruptions, such as strikes, due to the low inventory coverage.

Inventories cannot be avoided altogether; in many industries they are necessary in order to provide rapid solutions to operational problems or emergencies. In these businesses there is a large-scale centralisation of storage facilities, typically one or two for the whole of Europe, often situated at or near airline hubs. This system is cost-effective from an inventory management point of view, but the hub and spoke system will further add to the increase in transportation needs.

A related development is taking place within the production facilities themselves, where ICT developments are enabling the rapid growth of large-scale production-to-order processes. One of the pioneering companies is Dell, which will only produce to order. Dell has one factory in Ireland covering all of Europe, with the capability of delivering any order within five days. The founder of the company, Michael Dell, has said: the issue is not how much inventory you have but how fast it moves. This approach, relying on flexible production techniques and efficient tools for handling orders,[30] has proved to be a superior overall solution, but from a transportation point of view it increases the number of deliveries and hence transport needs.

This trend towards shorter delivery cycles, along with the growing importance of high-value, low-volume products, has led to significant changes in the modal shares of freight transport in the OECD countries. Rail systems have so far been unable to deliver either the flexibility or the speed of delivery that this distribution philosophy requires. In the countries of western Europe there has thus been a substantial shift in freight patterns, with a decline in the volume of freight carried by rail and a 50 per cent increase in road freight volumes in the period 1970-92.[31] The growth in air freight volume is even more impressive, with an almost 7 per cent compound annual growth rate globally.

The ICT revolution has so far enabled the implementation of new production and distribution techniques (JIT, etc.) that increase the need for transportation. In the future, it is expected that the digitalisation of the economy, along with new teleworking practices, will provide an opportunity to break this trend. The future deployment of IVHS systems, possibly in combination with road pricing systems, could provide an additional impetus towards a more energy-efficient transport system – possibly reducing the energy requirements by as much as 20 per cent compared to a business-as-usual development.

## 4. Summary and conclusions

The energy industry makes two contributions to mankind: to the wealth and economic welfare of all citizens, and to the world's environmental problems. A development based solely on the maximisation of wealth and short-term welfare will not be ecologically sustainable. On the other hand, development based solely on the minimisation of environmental impact will not be socially sustainable. Again, there is no one magic formula.

Given the consumer trends driving the energy market, strong underlying energy demand growth is likely to continue into the foreseeable future. Although the effects of demand saturation will gradually influence developments in the OECD countries, the vast pent-up demand of the 3 billion people yearning for the basic necessities of life will overwhelm any localised saturation tendencies.

Although the current trend points toward a future with continued growth in energy consumption, this trend can be broken.[32] Whether or not that actually happens will depend on a series of developments, the most important of which are:

– the speed of technological change;

– developments in consumer tastes and lifestyles;

– the regulatory framework.

This chapter identified heat pump technologies as having the potential to revolutionise the efficiency with which heat is produced for the stationary sector. In the transport sector a series of parallel developments are envisaged; both fuel cell cars and hybrid cars, in combination with better car design, might have the potential to double the energy efficiency of transportation. ICT, meanwhile, could revolutionise infrastructure systems and the way we commute and shop. The technologies that are ultimately realised in the market-place might take account of this potential and in any case will most probably also include hitherto unimagined new products.

Although the potential for efficiency improvements through technological improvements is substantial, it must be remembered that people use energy through the application of technology to satisfy their basic need for comfort, mobility, etc. Lifestyles and consumer tastes thus play an essential role in the development of the future energy balance.

Authorities wishing to encourage the transition towards a more energy-efficient economy will therefore have to adopt policies and a regulatory framework targeted at both technology and consumer lifestyles. A concerted research effort will therefore have to be pursued in order to further enhance our understanding of the nature and magnitude of the sustainability challenges related to energy use. However, in order for this research effort to be politically viable, all stakeholders must be involved in the policy discussions. Furthermore, any policies adopted must be open to the forces of innovation, encouraging non-discriminatory and open access to the market for inventors and entrepreneurs with bright new ideas. Finally, the regulatory framework governing all economic activity must encourage the increased penetration of flexible working practices, enabling a more widespread adoption of teleworking and telecommerce.

## Notes

1. At purchasing power parity.
2. Source: World Bank, World Development Indicators, 1998.
3. Source: IEA World Energy Balances for 1995.
4. Centrally planned economies.
5. Source: IEA Energy Balances, 1997.
6. According to the UN, less than 30 per cent of the population of China and India live in urban areas.
7. Although the use of electric vehicles will increase the efficiency of energy use in the transport sector, through the higher transformation efficiency of stationary power plants compared to mobile car engines, the authors have chosen not to expand on this discussion here.
8. If the hydrogen is produced onboard the vehicle in a reformer converting gasoline or methanol to hydrogen, a 70 per cent efficiency could be expected. With an electrical efficiency of 90 per cent, the total efficiency would be the product of the three efficiencies, 25 per cent. This would not be much higher than the efficiency of today's passenger car engines and slightly lower than the future efficiency of the hybrid vehicles with a small engine running at optimum load and speed.
9. UHB engines have a bypass ratio of 15-20, compared to 6-7 for HB engines.
10. The Statoil main office can serve as an example of the importance of this energy source. The energy from people, electronic equipment and light is so great that there is no need for additional heating of interior offices once the outside temperature rises above the freezing point.
11. Under Norwegian building standards, the transmission loss through windows is around 5 times as great as through a similar wall area.
12. According to the laws of thermodynamics, the only way to transport energy from a lower to a higher temperature level is through the use of a refrigerant.
13. Source: Energidata a.s., anvendelse av varmepumper - rammebetingelser, 1990.
14. With the exception of transport services.
15. International Data Corporation (IDC), February 1997.
16. Morgan Stanley.
17. Source: Statistics Norway, Norges Offisielle Statistikk, Forbruksundersøkelsen 1994.

18. This report was to a large extent written using online communication and application-sharing between Statoil departments in Stavanger and Trondheim.

19. There is no set definition of telework, which explains why estimates of its prevalence vary considerably between different sources. The phenomenon is loosely defined by the International Labour Office as the combination of information and communication technologies with the concept of a flexible workplace.

20. *Business Quarterly*, Spring 1993.

21. The Institute for the Study of Distributed Work estimated 4-5 million, LINK Resources 6.6 million, and the Yankee Group 8.8 million.

22. Gartner Group, "Key Trends and Drivers of Telecommuting", 6 May 1998.

23. J. Kr. Steen Jacobsen, T.E. Julsrud, J.I. Lian: "Telework and Potential Reduction in Work Travel", TØI working report 1024/1996, 1996.

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25. Since the home office project is termed a pilot project, these results might not be totally representative. This issue therefore needs to be analysed in greater detail.

26. One of the interesting results of the survey is that almost 50 per cent of the respondents see an increase in productivity as a consequence of having the ability to work from home.

27. The system allows for the inclusion of different types of road pricing, although these are not an integral part of IVHS.

28. By the Diebold Institute for Public Policy Studies, 1992.

29. Mainly related to congestion problems.

30. The majority of orders are now made via the Internet.

31. Source: European Conference of Ministers of Transport (ECMT).

32. Although the impact of large-scale war or conflict on economic activity and energy demand is acknowledged, that kind of scenario has not figured into the present discussion.

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# Systems Options for Sustainable Development[1]

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## 1. Introduction

The current global imbalance of energy supply and demand, coupled with the environmental consequences of carbon emissions, is causing mounting concern for the sustainability of our future development. While rapid economic growth in developing countries stimulates the world economy, it also increases pressures on energy supply and the environment. One answer to this predicament is to find appropriate solutions based on systems options, incorporating advanced technologies, that can help to overcome energy and environmental constraints while maintaining sustainable development.

New Earth 21 (Action Program for the 21st Century), proposed by Japan in 1990, offers comprehensive, long-term systems options that aim at restoring global environment conditions to a level equivalent to that before the Industrial Revolution in the 18th century, and suggests possible ways to progress toward "no-regret" options. Although there are many studies that endeavour to solve these problems, the majority focus on the technical dimensions of individual energy technologies; no substantial work focuses on *systems* dimensions.

In light of the increasing importance of identifying the most appropriate systems options, this chapter analyses the future of energy technologies on the basis of the concept proposed by New Earth 21.

The first thing to recognise in any such analysis is that the issue in question emerges from the crossroads of energy and technology. In addition to the increasing uncertainty of energy supply and demand in the geopolitical context of the 21st century, technology decisions will need to take on board the complexity of interactions among social, economic, cultural and institutional circumstances. The point of intersection between technology and energy is in fact no mere point but a dynamic system involving both the economy and the environment. Furthermore, this system is becoming a sensitive and controversial area as the dynamics are played out.

Section 2 of this chapter undertakes a brief review of the future energy technologies in six categories that comprise the principal elements of New Earth 21. Based on those findings, Section 3 elucidates key dimensions of energy technology strategies for the 21st century. Section 4 attempts to relate those dimensions to systems options strategies essential for attaining the New Earth 21 goal, by demonstrating Japan's own systems option success. Section 5 briefly summarises the main messages obtained from the analysis.

## 2. A brief review of future energy technologies

This review was conducted from the perspective of systems options. The technologies were broken down into six categories comprising key elements of New Earth 21 as summarised in Figure 1 and Table 1. The six categories examined are: *i)* end-use energy technology, *ii)* renewable energy technology, *iii)* nuclear fission technology, *iv)* technology aimed at cleaner use of fossil fuels, *v)* innovative technologies for $CO_2$ treatment and *vi)* nuclear fusion technology.

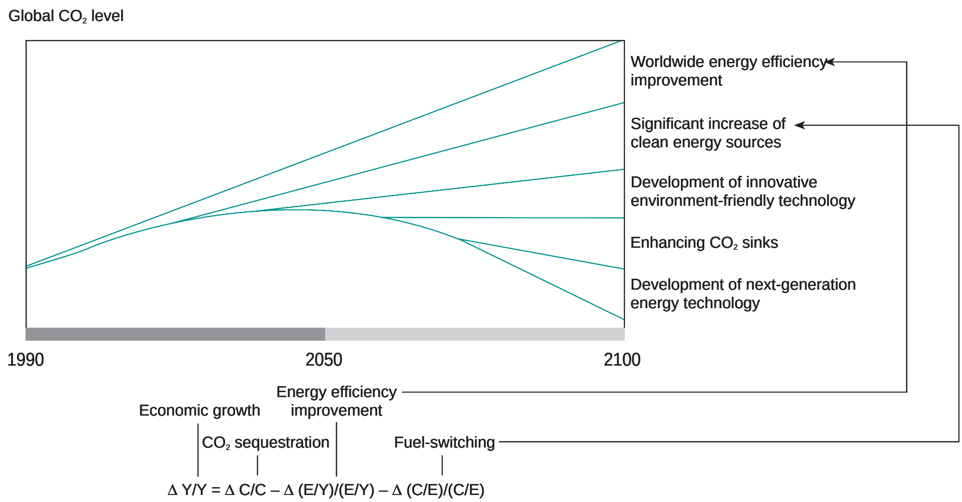
The review was based primarily on the International Energy Agency's report on energy technologies for the 21st century (IEA, 1997) and focused on technology priority, technology prospects and possible markets trends, and the significance of technological breakthroughs and subsequent international spillover effects.

### *End-use energy technology*

#### *Potential*

Energy efficiency improvement, in terms of energy productivity, conservation, or both, is being seen increasingly as a promising strategy for attaining simultaneously the goals of energy security, environmental protection and sustainable growth. While there remains a vast potential, technically, for further efficiency increase, a stagnating trend *vis-à-vis* improvement in advanced countries has been observed due to the decrease in marginal productivity of energy and declining international oil prices. In addition, the mechanism for incorporating energy efficiency improvement in the socio-economy of developing countries has proved inadequate. Bold and innovative approaches are required if the full technical and economic potential for increased energy efficiency is to be realised.

Figure 1. **General concept of New Earth 21**




*Source:* Author.

Table 1. **General concept of New Earth 21**

Actions and major technological breakthrough fields

| Actions for New Earth 21 | Major technological breakthrough fields |
|---|---|
| A Worldwide energy efficiency improvement | 1. End-use energy technology |
| B. Significant increase of clean energy sources | 2. Renewable energy technology (RET)<br>3. Nuclear fission technology<br>4. Cleaner use of fossil fuels technology |
| C. Development of innovative environment-friendly technology | 5. Innovative technology for $CO_2$ treatment ($CO_2$ capture, disposal and recycling) |
| D. Enhancing $CO_2$ sinks | |
| E. Development of next-generation energy technology | 6. Nuclear fusion technology |

*Priorities*

Technology priority goals are:

*1.* enhancing the demonstration and market deployment of existing technologies to improve the efficiency, economics, and flexibility of energy use;

*2.* encouraging further development and application of next-generation technologies with a view to maximising their potential environmental benefits, including reduction of greenhouse gas emissions.

*Prospects*

Energy markets work best when they are competitive and when trade and investment distortions are limited. However, there are many technical and institutional barriers, which may discourage R&D efforts and limit technological progress. Market forces alone are unlikely to bring about the level of efficiency improvement implicit in most environment-oriented energy policies seeking to stabilize and reduce greenhouse gas emissions.

*Spillovers*

Governments have a major role to play in removing barriers and bridging the gap between technical opportunities and decisions by individual consumers. In particular, government-industry projects focusing on the demonstration of innovative energy-efficient processes in energy-intensive industries need to be encouraged.

The effects of energy efficiency improvement could be maximised through inter-sectoral technology spillovers, particularly those from high-technology industries to energy-intensive industries. Government-industry projects could and should stimulate such spillovers.

Similar technology spillovers should be realised at a global level. Governments in advanced countries could thereby stimulate improvements in energy efficiency in developing countries.

### *Renewable energy technology*

*Potential*

While the potential varies among renewable energy technologies, their capacities are for the most part large – precisely because they use resources generally not subject to depletion.

New and improved technologies with different technical and economic attributes, degrees of maturity, and potential in future energy systems are now being developed and tested.

Intensive work by government and industry over the past fifteen years in particular has steadily increased the performance of renewable energy systems, leading to a dramatic decrease in their costs. Some renewable energy technologies could become commercially competitive with conventional resources. In addition, the newly emerging challenge to construct an international clean energy network using hydrogen conversion is expected to contribute to a dramatic increase in worldwide renewable energy over the medium and long term.

*Priorities*

To exploit their potential, the following goals have been identified:

1. improving the efficiency and economic viability of renewable energy systems;
2. expanding their deployment and effective integration into existing or evolving energy systems;
3. constructing a virtuous cycle between improvement of economic viability and expansion of deployment;
4. constructing an international clean energy network using such converters as hydrogen.

*Prospects*

While the technical potential of renewable energy is considerable, it makes a relatively small energy contribution due to its present state of development. Current energy economics, market factors and institutional constraints compound this. Generally, renewables face significant barriers to market entry – such as lack of infrastructure, relative technical and economic immaturity, inadequately demonstrated reliability and maintainability, and a need for economies of scale in component manufacture and deployment techniques.

However, if national and social factors such as environmental and security concerns were internalised in energy system costs, the economic potential of renewables would improve and their contribution would grow significantly.

Furthermore, a system approach which attempts to synthesise a variety of possible innovative technologies into an international clean energy network using hydrogen conversion could lead to an extremely high-level breakthrough.

*Spillovers*

Governments should focus on: *i)* constructing a virtuous cycle by means of selecting and continuing R&D to reduce costs and improve the performance and efficiency of emerging renewable energy technologies and systems, *ii)* institutional improvement, *iii)* inducing industry's involvement in these efforts, and *iv)* facilitating international co-operation toward, *e.g.*, constructing an international clean energy network.

### *Nuclear fission technology*

*Potential*

Nuclear fission energy continues to make a substantial contribution to the diversification of energy supplies. Uranium reserves are abundant and widespread. The technology emits no greenhouse gases in power generation, and thereby meets a number of environmental requirements.

However, concerns about nuclear accidents, waste and proliferation may limit the full exploitation of the advantages of nuclear fission energy. These concerns need to be addressed if the nuclear option is to be maintained and its deployment prospects enhanced.

*Priorities*

The priority goals for nuclear fission energy are:

1. developing and deploying economically competitive nuclear power-generating technologies with standard or modular designs while maintaining and enhancing safety;
2. developing and deploying acceptable nuclear waste management technologies and systems;
3. widening the safe applicability of nuclear fission energy, and expanding its resource base.

*Prospects*

Sustainable R&D efforts on further improving economy and safety, ensuring the safe disposal of nuclear wastes, and establishing technologies for more publicly acceptable decommissioning of nuclear power plants are continuing, and technically the prospects are good. However, the decisive factor for the introduction and development of nuclear power in some countries is broad public acceptability, rather than narrow techno-economic potential. Therefore, future market trends of nuclear power depend on how techno-economic development and operating results of nuclear power enhance public acceptability.

*Spillovers*

The future of nuclear power is heavily dependent on government: its activities to reduce the market risks of demonstrating new technologies, its direct support for specific projects, and its indirect support through measures such as streamlining regulatory principles and practices, and their international harmonization.

However, government policy and regulations alone are not enough to ensure the continued viability of nuclear power. It is the responsibility of industry to ensure that nuclear plants are operated safely and economically, and that the public has full access to information on this technology.

### *Cleaner use of fossil energy technology*

*Potential*

Of all fossil fuels, coal has the largest resource base by far and the highest reserves-to-consumption ratio. It is a key component of worldwide energy security due to its abundance, widespread geographic distribution, relatively low cost and price stability, and its ready availability in an established and competitive international market.

On the other hand, oil remains particularly important to advanced countries – especially with regard to transport – and demand for it continues to rise. Consumption of natural gas as a fuel is also growing because of its convenience, economic advantages, and what are perceived as comparative environmental benefits.

*Priorities*

Priority goals for coal, oil and natural gas in technological terms are:

1. improving coal's conversion efficiency, environmental acceptability, and economic viability as a competitive energy source;
2. diversifying clean uses of coal with a view to maintaining flexibility and coping with changing energy needs in the long term;
3. increasing access to economically exploitable oil and natural gas reserves;
4. reducing the environmental effects and risks involved in hydrocarbon production.

*Prospects*

New and improved technologies for controlling conventional polluting emissions and their consequences are available or in the advanced demonstration stage.

However, the majority of technologies that could reconcile the energy and environmental dimensions of coal use while maintaining the fuel's economic competitiveness are next-generation technologies currently at intensive R&D, demonstration or testing stages.

Continuing emphasis has been placed on environmental protection as an integral part of technology development in order to enhance the international oil and natural gas supply.

*Spillovers*

There is considerable scope for direct government support and for government-industry technology collaboration to reduce uncertainty over performance characteristics, reduce costs, and improve commercial operation and the prospects of demonstrated and next-generation clean coal technology and power systems. Such collaboration could minimise the risks involved in large first-challenge projects, and ensure adequate R&D on longer-term options, including synthetic fuels. Government should also facilitate timely institutional arrangements for technology development and deployment by industry. Taking initiatives to encourage international collaboration and global spillovers of technology is another key government responsibility.

For oil and natural gas, given the relative maturity of the industry, the most significant government actions to facilitate progress would appear to be associated with promoting opportunities for high-risk, high-impact technology breakthroughs; enhancing safety and environmental protection; ensuring adequate scientific and engineering capability; and promulgating market-based regulations and policies to enhance investment and promote risk-taking by the industry in responding to market needs.

### *Innovative technology for $CO_2$ treatment*

*Potential*

In addition to technological development for mitigating greenhouse gas emissions by means of energy efficiency improvement and fuel-switching, technological breakthroughs for capturing emitted $CO_2$ and for disposing of as well as recycling captured $CO_2$ are expected to make significant contributions toward achieving the New Earth 21 goal.

*Priorities*

The priority goals with regard to innovative technology for $CO_2$ treatment are:

*1.* $CO_2$ capture technology such as chemical and biological fixation;

2. $CO_2$ disposal technology – disposal of the captured $CO_2$ by injection into oil fields, natural gas fields and underground aquifers, and ocean storage;
3. $CO_2$ recycling technology – recycling captured $CO_2$ by converting to methanol synthesis.

*Prospects*

The bulk of R&D in these innovative technologies was not undertaken until the 1990s, so they are still in the initial R&D-to-demonstration stages. Although there remains some uncertainty, these technologies are expected to be in practical use from 2020 to the middle of the 21st century.

*Spillovers*

R&D in innovative technology for $CO_2$ treatment – because of its enormous long-term public investment, its interdisciplinary nature and huge potential global returns – requires strong and consistent government initiatives and international collaboration. Such initiatives should focus on constructing an effective mechanism for inducing innovative technological breakthroughs and their international spillovers.

### *Nuclear fusion technology*

*Potential*

Nuclear fusion, with its many potential advantages as a non-exhaustible energy resource, is an important element of the long-term energy strategy for achieving the New Earth 21 goal.

Successful application of practical fusion technologies at some point in the 21st century could help enhance global energy security, provide an environmentally acceptable alternative to fossil fuel combustion, and contribute to continued economic growth through reliable electricity supply.

*Priorities*

The technology priority goals for nuclear fusion are:

1. continuing efforts geared towards demonstration of the technical feasibility of nuclear fusion power systems;
2. assessing the potential impact of fusion power on future energy supply.

*Prospects*

Nuclear fusion technology is still under development. The rate of progress will be determined by the building and operating in sequence of a number of devices which aim at demonstrating the feasibility of high magnetic fields and very high plasma densities, leading to a large-scale experimental reactor and then to a pilot-scale demonstration plant.

Nuclear fusion, while not likely to be a widely available power source in the next fifty years, could prove the ultimate solution for power generation in the latter half of the 21st century.

*Spillovers*

Fusion R&D, because of its massive long-term investment and correspondingly huge potential for global returns, requires adequate, sustained government support and international collaboration.

## 3. Key dimensions of energy technology strategies for the 21st century

The above review of future energy technologies suggests that, given consistent efforts and reasonable sustained government initiatives, energy technologies in the major categories – particularly end-use energy, renewable energy, nuclear fission and cleaner use of fossil fuels – hold real promise, and have sufficient potential for market compatibility. Attaining the New Earth 21 goal by delivering on that promise depends to a large extent on systems dimensions rather than individual technical dimensions. One critical requirement is an effective mechanism for inducing innovative technological breakthroughs and international spillovers from these breakthroughs. More specifically, the success of the initiative requires a timely construction of *i)* a virtuous cycle for technology in its social, economic and natural environments in a global context, and *ii)* a system for maximising potential biased in particular countries/regions by global technology spillover.

Another indispensable element is complementarity. The systems options for overcoming energy and environmental constraints while also maintaining sustainable development can be simply considered a dynamic interaction of Three E's: economy, energy and environment. Provided that these Three E's can be represented by production (Y), energy consumption (E) and $CO_2$ emissions (C), this dynamic can be represented by a simple equation, illustrated at the bottom of Figure 1.

Thus, an appropriate option based on the systems solution is to find the best combination of the three possible options: energy efficiency improvement, fuel-switching and CO2 sequestration. New Earth 21 navigates long-term systems options over the next century by demonstrating energy/environmental technologies corresponding to the choices above. For example, the major options over the next fifty years might include “worldwide energy efficiency improvement” for the energy efficiency improvement option, “significant increase of clean energy sources” for the fuel-switching option, and “development of innovative environment-friendly technology” for the CO2 sequestration option.

Table 2 summarises a comparison of this dynamic systems interaction in Japan, the United States, Western Europe, the former USSR and Eastern Europe, and the less developed countries (LDCs) in the ten years following the second energy crisis (1979-88). Japan recorded the highest economic growth, with an average annual GDP growth rate of 3.97 per cent. Such growth was possible due to a 3.44 per cent energy efficiency improvement and a fuel-switching rate of 0.59 per cent, together with a 0.06 per cent decline in CO2 emissions. (The first two figures can be seen as contributing to the third.) The LDCs followed Japan in terms of GDP growth, with an average annual rate of 3.53 per cent. During the ten-year period, fuel-switching had a positive effect as it rose by 0.16 per cent. However, energy efficiency fell by 0.85 per cent, leading to a 4.22 per cent increase in CO2 emissions. The United States attained 2.78 per cent average annual GDP growth, supported by a 2.62 per cent energy efficiency improvement and a 0.11 per cent rise in fuel-switching. CO2 emissions increased by 0.05 per cent. In Western Europe, GDP growth measured 2.01 per cent as energy efficiency improved by 1.78 per cent, fuel-switching increased by 1.33 per cent and CO2 emissions decreased by 1.10 per cent. Average annual GDP growth in the countries of the former USSR and Eastern Europe was 1.72 per cent. Energy efficiency declined by 0.45 per cent while fuel-switching rose 0.83 per cent; emissions of CO2 increased by 1.34 per cent.

Table 2. **Comparison of paths in attaining development in major countries/regions in the world (1979-88)**

Average change rate: % per annum

| | Production[a] (EY/Y) | Energy efficiency (E(E/Y)/(E/Y)) | Fuel-switching (E(C/E)/(C/E)) | $CO_2$ emissions (EC/C) |
|---|---|---|---|---|
| Japan | 3.97 | –3.44 | –0.59 | –0.06 |
| United States | 2.78 | –2.62 | –0.11 | 0.05 |
| W. Europe | 2.01 | –1.78 | –1.33 | –1.10 |
| USSR/E. Europe | 1.72 | 0.45 | –0.83 | 1.34 |
| LDCs | 3.53 | 0.85 | –0.16 | 4.22 |

*a)* *Production* is represented by GDP.

*Sources :* Y. Ogawa by using IEA's IEA Statistics, Energy Balances of OECD Countries, and Energy Statistics and Balances of non-OECD Countries, 1992.

The relative advantage and disadvantage of energy efficiency improvement and fuel-switching are generally governed by the economic, industrial, geographical, social and cultural conditions of a country or region. Japan's notable achievement in realising an improvement in energy efficiency, given that it is an energy-importing, trade and technology-based nation, was initiated by industry as part of its survival strategy so as to be free from the burden of energy cost. However, due to geological constraints and dependency on coal as an oil-substituting energy, the fuel-switching capability was limited. This was not the case in Western Europe, where nations had the geographical advantage of being able to rely on readily available natural gas and biofuels – and where the efforts of industry towards energy efficiency improvement were not as strong.

This review suggests that if the experience and expertise of particular countries/regions with comparative economic, geographical and/or social advantages could be transferred to other countries/regions with comparative disadvantages, the Three E conditions of the recipients could be dramatically improved, leading to global improvement in the Three E's.

## 4. Empirical demonstrations of successful systems options

In order to relate key dimensions of energy technology strategies for the 21st century discussed in the previous section with system option strategies essential for attaining the New Earth 21 goal, empirical demonstrations of Japan's system option success have been conducted. These focused on the areas of *i)* energy efficiency improvement in the manufacturing industry; *ii)* construction of a virtuous cycle among R&D, demonstration, diffusion and deployment in PV development; and *iii)* inter-sectoral technology spillover in high technology essential for dramatic energy efficiency improvement in energy-dependent sectors.

### *Systems mechanism for energy efficiency improvement in the manufacturing industry*

Despite the fragile nature of its energy structure, Japan successfully overcame two energy crises in the 1970s, and managed to maintain economic growth that resulted in a dramatic improvement in industrial technology – giving rise to a virtuous cycle. The success of these efforts can be attributed to appropriate solutions based on systems options, particularly to technology options: technology substitution for energy. Japan's Ministry of International Trade and Industry (MITI)'s industrial technology policy functioned well in generating the vitality in industry that was necessary for such substitution. Nevertheless, following relaxation of energy constraints, the so-called "bubble economy" that followed and its bursting, MITI's policy ability in this area weakened, leading to fears of a collapse of the virtuous cycle between technology and economic development.

*Systems options*

As demonstrated in the comparison in Figure 1, Japan's success in the 1970s and 80s in overcoming energy and environmental constraints while maintaining sustainable growth can largely be attributed to industry's intensive efforts towards energy efficiency improvement. Despite numerous handicaps, Japan's economy successfully achieved sustainable development by focusing on efforts to improve the productivity of relatively scarce resources. This included capital stock up until the 1950s, followed by the supply of labour, environmental capacity constraints, and the energy supply after the first energy crisis in 1973. The development of the manufacturing industry proved to be the driving force behind this achievement. In addition, technology development played a key role in the rapid enhancement of productivity levels through its successful substitution for a limited resource such as energy.

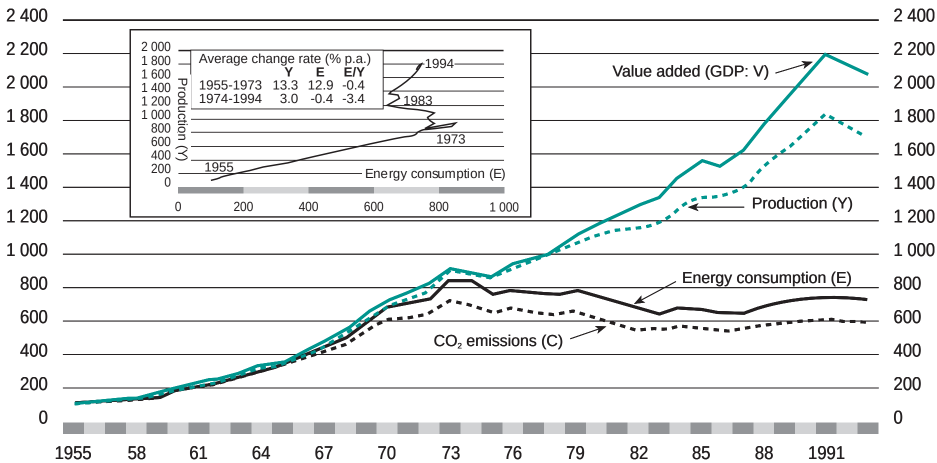
During the years 1955-73, the period before the first energy crisis, Japan's manufacturing industry enjoyed 13.3 per cent growth per year, largely supported by a cheap and stable supply of energy. During that period the average increase in the rate of energy dependency was 12.9 per cent per year, while the rate of change in energy efficiency was only –0.4 per cent per year. In contrast to this, during the years 1974-94, Japan's manufacturing industry achieved a notable energy efficiency improvement of 3.4 per cent per year. Therefore, it was able to enjoy an average 3.0 per cent per year production increase (GDP growth was 4.1 per cent) while minimising energy dependency at –0.4 per cent, as illustrated in Figure 2. The figure shows that despite the damaging impact of the energy crises, industry was able to maintain steady development and increase production while keeping energy consumption and $CO_2$ emissions to a minimum.

Chart 1 (see Annex) analyses factors contributing to change in $CO_2$ emissions in the manufacturing industry over the period 1970-94. The chart demonstrates that while the average annual increase in production by value added between 1974 and 1994 was maintained at a reasonable level of 4.06 per cent, the average for $CO_2$ emissions fell by 0.71 per cent. Chart 1 also indicates that 71 per cent of this reduction in $CO_2$ can be attributed to efforts to improve energy efficiency, while 22 per cent can be attributed to change in industrial structure. The contribution of fuel-switching was only 4 per cent. This analysis coincides with the previous examination and confirms that Japan's success in attaining environmentally friendly sustainable development after the first energy crisis depended largely on the results of efforts to reduce energy dependency.

If $CO_2$ discharge trends and contributing factors are examined at different times, it can be seen that the discharge level decreased dramatically after 1973 as energy efficiency improvement efforts increased. This is largely the result of

Figure 2. **Trends in production, energy consumption and $CO_2$ discharge in the Japanese manufacturing industry (1955-94)**

Index 1955 = 0.1




*Source:* Author.

substituting technology (energy conservation technology) and capital (energy conservation facility) for energy. On the other hand, the contribution of fuel change (which also represents the outcome of similar substitutions involving oil-alternative technologies and capital investment) is much less significant due to an increase in dependency on coal as a promising oil-alternative energy.

A careful look at these trends reveals that $CO_2$ discharge increased after 1983 (the start of the fall of international oil prices) due to an increase in coal dependency and a decrease in energy efficiency improvement efforts. Since 1987 (the start of the "bubble economy"), those efforts have significantly decreased further, leading to increased $CO_2$ emissions. Although from 1991 $CO_2$ discharge decreased again, this is due solely to a decrease in GDP that resulted from the bubble bursting – energy efficiency improvement efforts have continued to decline, resulting in a change in the energy-intensive mode.

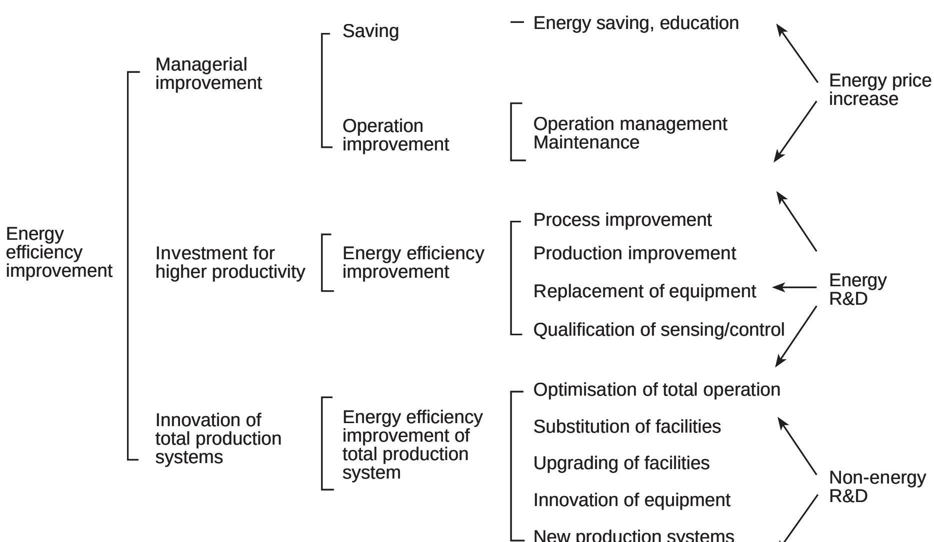
*Contribution of technology options*

Japan's success in attaining environmentally friendly sustainable development after the first energy crisis in 1973 depended largely on the results of efforts to reduce energy dependency. This was accomplished by means of an improvement in energy efficiency chiefly initiated by the industrial sector, meant to counter the sharp increase in energy prices caused by the energy crises. The response first focused on managerial improvement by means of energy-saving education, operational management and maintenance efforts.

Once it was clear that these efforts had achieved their maximum effect, the next step was investment for higher productivity: buying, installing, equipping and replacing improvement facilities and sensing/control equipment systems for increasing the efficiency of complicated flows of energy, materials and semi-processed products. As energy prices continued to increase sharply after the second energy crisis in 1979, these efforts too reached their maximum effect, and the industry moved on to the next step: innovation of total production systems, as illustrated in Figure 3.

The latter two steps were possible due largely to technological innovation in conservation facilities, production processes, sensing and control systems, and new production systems. This was Japan's survival strategy in a constrained economic environment: substitute a constraint-free production factor such as technology for a constrained one such as energy.

Figure 3. **Measures for energy efficiency improvement in industry**




*Source:* Author.

Change in energy efficiency results from a dynamic interaction between initial changes in energy dependency and production based on dependable energy. Technology generally has a significant impact on changes in energy and production. Therefore, the technology contribution to energy efficiency improvement relates to how it maximises production while minimising energy used. In this particular case, technology can be divided into two categories, energy and non-energy. While non-energy technology aims primarily at maximising production, energy technology focuses on conservation and supply, and aims primarily at minimising energy dependency (chiefly on oil).

Non-energy technology interacts largely with capital to increase production – a complementary relationship. However, increasing capital for a production increase inevitably results in increasing energy use. Energy technology, on the other hand, interacts largely with capital for an energy efficiency improvement (also a complementary relationship), thereby making a significant contribution to reducing energy dependency (capital substitution for energy). Although it also stimulates a production increase, the magnitude is relatively small.

The contribution of technology to energy efficiency improvement can be considered a dynamic interaction chiefly among the above actors: non-energy technology with capital for a production increase; energy technology with capital for energy efficiency improvement; energy; and production, as illustrated in Figure 4.

In order to produce a quantitative analysis of the dynamic interaction with respect to the technology option and its contribution to energy efficiency improvement, the author measured both energy technology (TE) and non-energy technology (TnE) by calculating the technology knowledge stock of energy R&D and non-energy R&D with a dynamic rate of obsolescence of technology and the time lag of R&D to commercialisation.

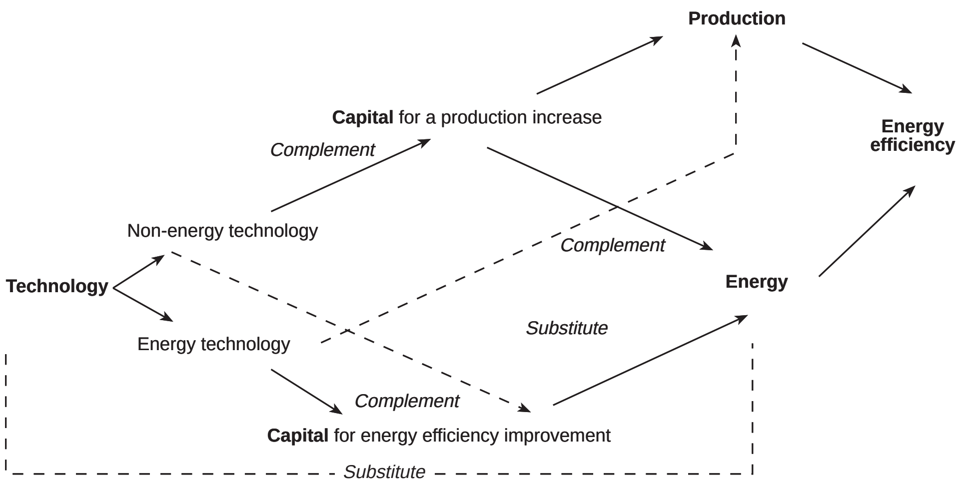
The result of the measurement is illustrated in Chart 2 (see Annex):

*1.* The priority in R&D shifted from non-energy to energy R&D from the beginning of the 1970s in the Japanese manufacturing industry. This trend reflects the economic impact of the energy crises in 1973 and 1979; expenditure on energy R&D increased rapidly, particularly between 1974 and 1982. However, after international oil prices started to fall in 1983, energy R&D expenditure decreased dramatically.

*2.* Corresponding to these trends with a certain time lag, the technology knowledge stock of energy R&D increased dramatically during the period 1974-82, continued the increase in the period 1983-86, and declined dramatically from 1987.

*3.* That increase over a limited period (1974-86) resulted in a rapid increase in the rate of technology obsolescence (which increased from 15.4 per cent in

Figure 4. **Basic concept of the technology option for sustainable growth under energy constraints**




*Source:* Author.

1974 to 21.2 per cent in 1987), leading to a rapid decrease in the time lag of R&D to commercialisation (which decreased from 3.4 years in 1974 to 1.4 years in 1987).

On the basis of the findings in Chart 2, over the period 1974-94 the characteristics of industry energy R&D and the subsequent technology knowledge stock of energy R&D can be summarised as follows:

1. higher intersectoral factors common to all sectors other than non-energy R&D;
2. sensitivity to government R&D funding;
3. sharp inducement of energy efficiency improvement investment;
4. significant contribution to energy efficiency improvement;
5. dynamic change closely correlated with trends in energy prices.

Such characteristics suggest that the technology contribution to energy efficiency improvement in the manufacturing industry can be analysed by using the aggregated technology knowledge stock of energy R&D.

The results of the analysis are illustrated in Chart 3 (see Annex), which indicates that the manufacturing industry's achievement of a 3.4 per cent average annual improvement in energy efficiency over the period 1974-94 can be attributed as follows: 55.4 per cent to energy technology (technology knowledge stock of energy R&D), 24.9 per cent to non-energy technology, 8.0 per cent to other efforts in response to the sharp increase in energy prices, and 11.7 per cent to non-technology-oriented autonomous energy efficiency improvement.

These analyses support the aforementioned hypothesis that Japan, confronted with the damaging impacts of the energy crises, made every effort to substitute a constraint-free (or unlimited) production factor (technology) for a constrained (or limited) production factor (energy), as its survival strategy. They also furnish a warning that despite its success in overcoming energy and environmental constraints in the 1960s, 70s and the first half of the 80s, Japan's economy once again faces the prospect of energy and environmental constraints following the fall of international oil prices and the subsequent “bubble economy” and its bursting.

*The role of government*

R&D investment generally has various characteristics, including uncertainty, huge risk, high cost, and a long lead-time. Energy R&D has, in addition, a strong public nature, a close relationship with national security, and sensitivity to such opaque factors as trends in international oil prices. Thus, in order to induce industry's vigorous energy R&D investment, essential for a timely increase in technology knowledge stock, strong government policy involvement based on a long-term perspective is required. This is particularly the case in Japan, where the energy structure is extremely fragile compared to other advanced countries.

MITI, which is responsible for comprehensive energy policy and industrial technology policy, established an elaborate system for such inducement, which can be summarised as follows:

1. Encourage broad involvement of cross-sectoral industry in national R&D programme projects such as the Sunshine Project (new energy technology) and Moonlight Project (energy conservation technology) by stimulating the competitive nature of industry.
2. Promote cross-sectoral technology spillover and inter-technology stimulation.
3. Induce vigorous industry activity in the broad area of energy R&D, which would:
4. Increase industry's technology knowledge stock of energy R&D, further encouraging (2). MITI would thus:
5. Serve as catalyst in industry's substitution of technology for energy.

MITI's efforts towards that substitution have clearly boosted industry's energy R&D in terms of inter-technology stimulation and its cross-sectoral spillovers. These efforts combined led to Japan's energy development success in the 1970s and 80s.

What, then, of the current fears of energy and environmental constraints? The analysis in Chart 3 imputed this fear to the stagnation of energy technology (technology knowledge stock of energy R&D), itself a result of industry's stagnating energy R&D expenditure. In order to identify the sources of that stagnation, the author analysed factors governing the Japanese manufacturing industry's energy R&D expenditure over the period 1974-94. Chart 4 (see Annex) indicates that decreases both in MITI's energy R&D budget and in industry's total R&D expenditure, and the time lag of energy R&D to commercialisation, are major sources of the stagnation dating from 1983.

MITI's energy R&D budget was influenced by the amount of the Ministry's overall R&D budget, by trends in energy prices (the decrease in international oil prices), and by government finance constraints after the energy crises due to the decline of economic growth.

Later, post- "bubbleburst", Japanese industry faced a structural stagnation of R&D activities which resulted in a decrease in technology's contribution to economic growth. Subsequently, slower economic growth diminished the inducement of R&D investment. These trends have formed a vicious cycle between technology and economic development that could destabilize the virtuous cycle that has been in place.

The data furnish clear warnings of continuing stagnation with regard to the building of manufacturing industry's technology stock of energy R&D. That could lead to a breakdown of Japan's system of technology substitution for energy. MITI needs to take preventive action by providing effective policy measures to reactivate substitution efforts. Moreover, given the contrasting factors involved, MITI should develop an approach based on integrating R&D programmes – for new energy technology, energy conservation technology and global environmental technology – so as to alleviate concerns about sustainability. Energy and environmental constraints can both be overcome, simultaneously.

Towards those ends, MITI decided to establish the New Sunshine Program (R&D on energy and environmental technologies) in April 1993, by integrating the Sunshine Project, the Moonlight Project and the Global Environmental Technology Program. The New Sunshine Program is expected to make a significant contribution to attaining the New Earth 21 goal.

### *A virtuous cycle among R&D, demonstration, diffusion and deployment in PV development*

*Policy inducement*

Chart 5 (see Annex) illustrates trends in energy R&D expenditure by MITI and Japan's manufacturing industry over the period 1955-94. It also summarises an analysis of the stimulation impact of MITI's energy R&D (energy conservation and solar, coal, oil & gas, nuclear and electric power) on similar energy R&D initiated by the Japanese manufacturing industry. The chart indicates that the impact is significant, based on a one- to two-year time lag. The correlations of technology-driven energy R&D on energy conservation, renewable energy and coal technologies, led by both the Moonlight Project and the Sunshine Project, are distinctive; the correlations of R&D on technology development for diversifying energy sources (on oil/gas, nuclear energy and electric power) are somewhat less so. This analysis seems to confirm the above hypothetical views.

*Industrial dynamism of the virtuous cycle among R&D, market growth and price reduction*

Despite its major efforts in developing extensive renewable energy, Japan has not achieved comparative advantage in this field due to inherent constraints in the natural resources for renewable energy sources. One of the exceptions is photovoltaic power generation (PV).

The PV is considered to be a "footloose" renewable energy that can overcome Japan's own geographical disadvantages by means of technology breakthrough. It is expected to be put to practical use in the near future, and thereby contribute to a significant worldwide increase in clean energy. The Sunshine Project (R&D on new energy), initiated in 1974, aimed at developing technology-driven clean energy. However, its initial priority regarding solar energy R&D was solar thermal energy rather than PV. Since 1980, MITI has decided to focus R&D on PV in the project, on the basis of progress in semiconductor technologies and amorphous PV technology development. The New Energy & Industrial Technology Development Organization (NEDO), established in 1980 as MITI's affiliate responsible for the implementation and management of the Sunshine Project, undertook a major initiative with regard to this R&D; Figure 5 illustrates the budget trends as well as R&D expenditure for PV R&D initiated by industry and induced by the Sunshine Project.

Such efforts resulted in a dramatic increase in technology stock of PV R&D and a concurrent increase in solar cell production, as well as a decrease in production cost (Figure 6).

Figure 5. **Trends in R&D expenditure of PV R&D in Japan (1974-94)**

Index: 100 million yen at current prices

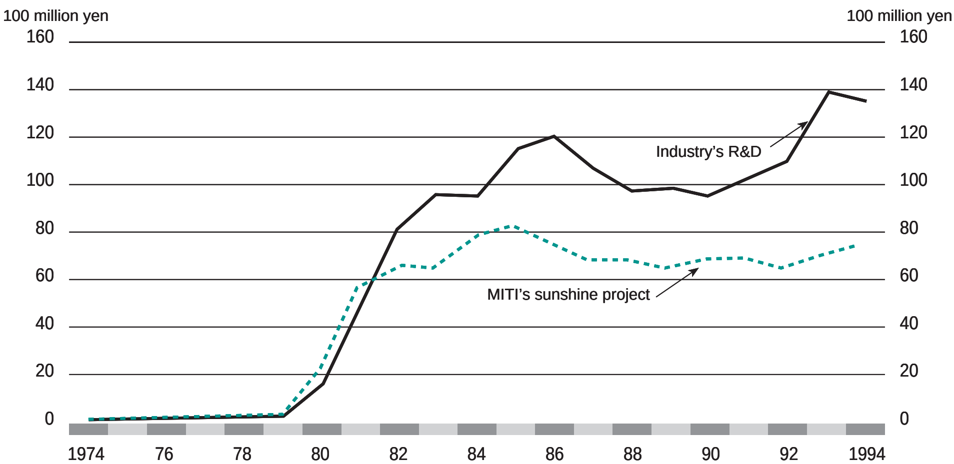
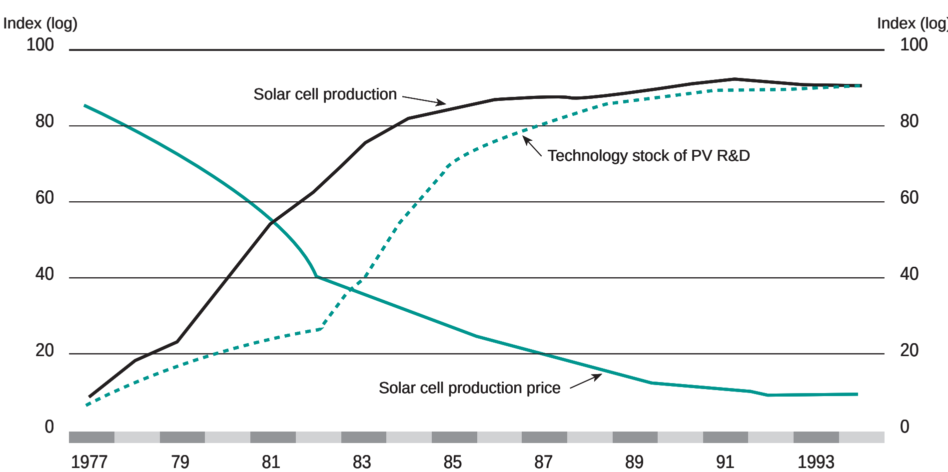



Figure 6. **Trends in PV development in Japan (1976-94)**

Index




*Source:* Author.

The solar cell production price in 1974, the year the Sunshine Project began, was 20 000 yen/w; it decreased to 5 000 yen/w in 1980, 2 000 yen/w in 1983, 1 200 yen/w in 1985, 650 yen/w in 1990, and 600 yen/w in 1994 (at current prices). This steady decrease was attributed to the increase in technology stock and a subsequent increase in solar cell production. The Sunshine Project's influence is analysed in Chart 6 (see Annex).

Encouraged by this progress, and inspired by PVs'contribution as a prospective technology-driven clean energy, MITI decided to accord priority to creating a virtuous cycle of PV development in the New Sunshine Program; PV R&D was accelerated from 1993, and incentives for practical use of PV systems were increased.

If renewables are to be moved forward as a prospective fuel-switching option for environmentally sustainable development, it is clearly important to formulate coherent policies aimed at unleashing the dynamic momentum of virtuous cycles involving market growth and price decreases for the relevant technologies.

### *Intersectoral high technology spillovers for energy efficiency improvement*

Table 3 enumerates 115 firms participating in the Sunshine and Moonlight Projects in 1992. It indicates that a significant number of leading intersectoral firms (one-half of the top 40 in R&D) participated in many of the projects, which suggests that transfers and spillovers of technology across projects and across firms have resulted.

Table 4 demonstrates a case of patent applications derived from the fuel cell R&D projects of the Moonlight Project. Noteworthy is that more than 60 per cent of the patents were applied for by the machinery industry, rather than energy-dependent industries such as electric power, city gas, oil and chemicals. This demonstrates an active technology spillover from high-tech industry to an energy-intensive industry.

Conspicuous energy efficiency improvement in the Japanese manufacturing industry was initiated chiefly by such energy-dependent industries as iron & steel and the chemical industry. Those industries share nearly 60 per cent of manufacturing's energy consumption, as illustrated in Chart 7 (see Annex). However, contrary to expectations, energy R&D expenditure in these industries was limited, showing only 4 to 11 per cent in iron & steel and 3 to 6 per cent in chemicals.

The opposite was true in high-technology industries, where energy R&D was extremely high. The expenditure share in electric machinery, for example, was 29 to 35 per cent and 27 to 40 per cent in transportation equipment. Meanwhile, the share of energy consumption in these industries was only 2.5 to 4 per cent.

Table 3. **Firms participating in the Sunshine and Moonlight Projects in 1992**

| | |
|---|---|
| **The Sunshine Project (61)** | |
| Chemicals (15) | 24 Asahi Chemical Industry Co., 29 Mitsubishi Kasei Co., Mitsui Toatsu Chemicals Inc., Kaneka Co., Daito Hoxan Inc., Japan Catalytic Chemicals, Nippon Steel Chemical Co., Idemitsu Oil Co., Tonen Co., Nippon Oil Co., Nippon Kyoseki Oil Co., Oil Resources Development, Sumitomo Coal Mining Co., Mitsui Coal Liquefaction |
| Ceramics (4) | 33 Asahi Glass Co., Kyocera Co., NGK Spark Plug Co., Shinagawa Refractories Co. |
| Iron & steel (7) | Nippon Steel Co., 33 Sumitomo Metal Industries Ltd., 26 Kobe Steel Ltd., NKK Co., 28 Kawasaki Steel Co., Japan Steel Works Ltd., Japan Metal & Chemicals Co. |
| Non-ferrous metals and products (5) | Sumitomo Electric Industries, Ltd., Sumitomo Metal Mining Co., Hitachi Cable Ltd., Mitsui Mining & Smelting Co., Osaka Titanium Co. |
| Machinery (20) | 3 Hitachi Ltd., 6 Toshiba Co., 35 Ishikawajima-Harima Heavy Industries Co., 12 Mitsubishi Industries Ltd., 10 Mitsubishi Electric Co., 38 Fuji Electric Co., 32 Oki Electric Industry Co., 15 Sharp Co., 17 Sanyo Electric Co., Ebara Co., Mitsui Engineering & Shipbuilding Co., 2 Matsushita Electric Industry Co., Yuasa Battery Co., Japan Storage Battery Co., Matsushita Battery Co., 1 Tokyo Motor Co., 8 Nissan Motor Co. |
| Public utilities (4) | EPDC, Tohoku Electric Power Co., Okinawa Electric Power Co., Tokyo Gas Co. |
| Construction (6) | JGC Co., TEC Electrics Co., Chiyoda Co., Kandenko Co., Ohte Development Co., Geothermal Technology Development |
| **The Moonlight Project (54)** | |
| Chemicals (3) | 24 Asahi Chemical Industry Co., 29 Mitsubishi Kasei Co., Ube Industries Ltd. |
| Ceramics (4) | 33 Asahi Glass Co., Kyocera Co., NGK Spark Plug Co., NGK Insulators Ltd. |
| Iron & steel (3) | 33 Sumitomo Metal Industries Ltd., 26 Kobe Steel Ltd., NKK Co. |
| Non-ferrous metals and products (5) | Sumitomo Metal Industries Ltd., Hitachi Cable Ltd., Fujikura Ltd., Showa Electric Wire & Cable Co., Furukawa Electric Co. |
| Machinery (23) | 3 Hitachi Ltd., 6 Toshiba Co., 35 Ishikawajima-Harima Heavy Industries Co., 12 Mitsubishi Industries Ltd., Kawasaki Heavy Industries Ltd., 10 Mitsubishi Electric Co., Fuji Electric Co., 17 Sanyo Electric Co., Ebara Co., Mitsui Engineering & Shipbuilding Co., Kubota Co., Yokogawa Electric Co., Murata MFG. Co., Maekawa Manufacturing, Aishin Seki Co., Daikin Industries Ltd., Sumitomo Precision Products Co., Hitachi Zosen Co., Niigata Engineering Co., Yammer Diesel, Yuasa Battery Co., Japan Storage Battery Co., Matsushita Battery Co. |
| Public utilities (11) | Hokkaido Electric Power Co., Tohoku Electric Power Co., 19 Tokyo Electric Power Co., Chubu Electric Power Co., Hokuriku Electric Power Co., Kansai Electric Power Co., Chugoku Electric Power Co., Shikoku Electric Power Co., Kyusyu Electric Power Co., EPDC, Osaka Gas Co. |
| Construction (5) | JGC Co., TEC Electrics Co., Chiyoda Co., Shimizu Co., Obayashi Co. |

*Notes:* Figures heading firms indicate orders of R&D expenditure in 1992 out of 40 firms (19 firms out of 40 participated).
Figures in parentheses indicate number of firms in respective sectors.

Table 4. **Number of patent applications derived from the Moonlight Project – the case of fuel cell R&D (January 1991-August 1994)**

| Sector | SOFC[a] | PEFC[b] |
|---|---|---|
| Chemicals and ceramics | 78 (10.9%) | 5 (3.5%) |
| Machinery | 436 (60.9%) | 98 (69.0%) |
| Energy (electric power, city gas and oil) | 132 (18.4%) | 5 (3.5%) |
| Government | 21 (2.9%) | 3 (2.1%) |
| Foreign participants | 41 (5.7%) | 3 (2.1%) |
| Others | 8 (1.1%) | 28 (19.7%) |
| Total 716 (100%) | 716[c] (100%) | 142 (100%) |

*a)* SOFC: Solid Oxide Fuel Cells (started from 1981).
*b)* PEFC: Polymer Electrolyte Fuel Cells (started from 1992).
*c)* Includes 23 utility models.
*Source:* Trends in Patent Applications (Patent Office, 1995).

This observation suggests that the technology knowledge stock of energy R&D accumulated in the electric machinery and transportation equipment industries spilled over to iron & steel and chemicals through interactions of personnel, capital goods and intermediate input. Such cross-sectoral technology spillover played a significant role in achieving conspicuous energy efficiency improvement in the Japanese manufacturing industry. Furthermore, MITI-initiated national R&D programme projects such as the Sunshine Project and the Moonlight Project functioned well in stimulating the cross-sectoral technology spillover.

Judging on the basis of the successful intersectoral technology spillovers discussed above, further efforts in this direction should be promoted globally.

## 5. Systems options for energy technologies in the next fifty years – implications

Key messages obtained from this analysis for identifying the most appropriate systems options for future energy technologies and achieving the New Earth 21 goal could be summarised as follows.

***Systems dimensions are crucial for energy technologies to attain the New Earth 21 goal.***

Attaining the New Earth 21 goal by ensuring the good technical prospects of energy technologies depends on systems dimensions rather than on technical dimensions. One critical requirement is an effective mechanism for inducing innovative technological breakthroughs and global spillovers of those breakthroughs.

The review of future energy technologies suggests the basic nature of technology in its social, economic, cultural, institutional and geopolitical interactions. Similar to a biological system, it emerges in these multi-layer interactions and grows, develops and matures through a virtuous cycle. It also stagnates, declines and reaches obsolescence when a virtuous cycle collapses.

***Global complementarity is indispensable for attaining the New Earth 21 goal.***

The systems option for overcoming energy and environmental constraints while maintaining sustainable development amounts to a dynamic interaction of Three E's: economy, energy and the environment. The key to this interaction is finding the best combination of the three possible options: energy efficiency improvement, fuel-switching and $CO_2$ sequestration.

The relative advantage and disadvantage of these options are generally governed by the economic, industrial, geographical, social and cultural conditions of a country or region. Global complementarity of the experience and expertise of countries/regions with comparative economic, geographical and/or social advantages could lead to global improvement in the Three E's.

***Construction and maintenance of a virtuous cycle would be crucial.***

Given the metabolic nature of technology, the construction and maintenance of a virtuous cycle for technology development in its social, economic, and natural environments are crucial.

Over the last four decades, despite many handicaps, Japan has achieved sustainable development by focusing its efforts on improving the productivity of the relatively scarce resources of each era, including energy and environmental capacity constraints in the 1970s and 80s. Technology played a significant role in this achievement. Furthermore, sustained development induced further technological development. Thus, similar to an ecosystem, Japan constructed an elaborate virtuous cycle between technology and economic development.

However, since the relaxation of energy constraints, sharp appreciation of the yen and the succeeding "bubble economy" and its bursting, Japanese industry has been facing a structural stagnation of R&D activities that may result in the collapse of that virtuous cycle. And as ecosystems demonstrate, once such a cycle begins to collapse, remedying the system becomes increasingly difficult.

An important dynamic governing this system is that effective virtuous cycles are constructed by creating positive interactions with systems in different layers. Such multi-layered interactions would inevitably depend on a sophisticated cycle embedded in a specific time scale.

***Satisfying certain conditions paves the way for securing energy over the next fifty years:***

*1.* a timely, orderly and systematic undertaking to construct and maintain a virtuous cycle;

*2.* sufficient complementarity towards global technology spillover;

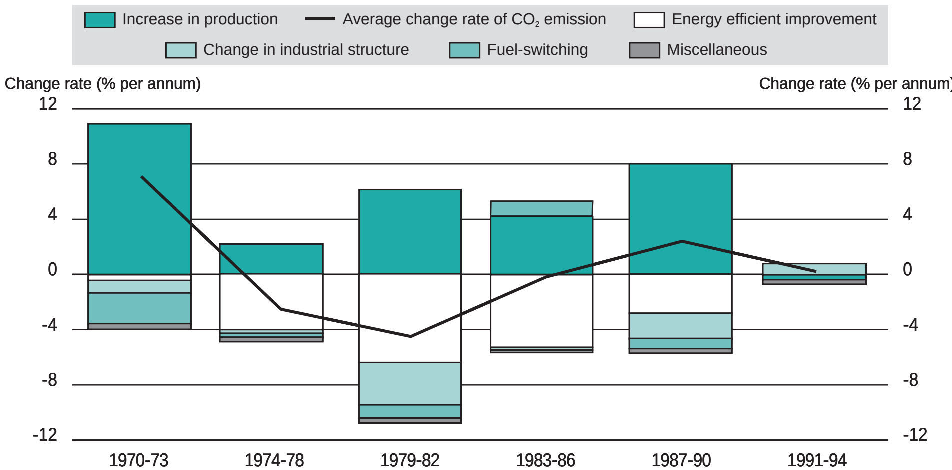
*3.* a broad involvement of actors towards integrating vitality and identifying respective responsibility-sharing.

## Notes

1. The author gratefully acknowledges the support of Kenneth Friedman and Clas-Otto Wene, IEA.
2. Professor Watanabe is also Senior Advisor to the Director on Technology, International Institute for Applied Systems Analysis (IIASA), and Chairman, EUWP, CERT, IEA.

# *Annex*

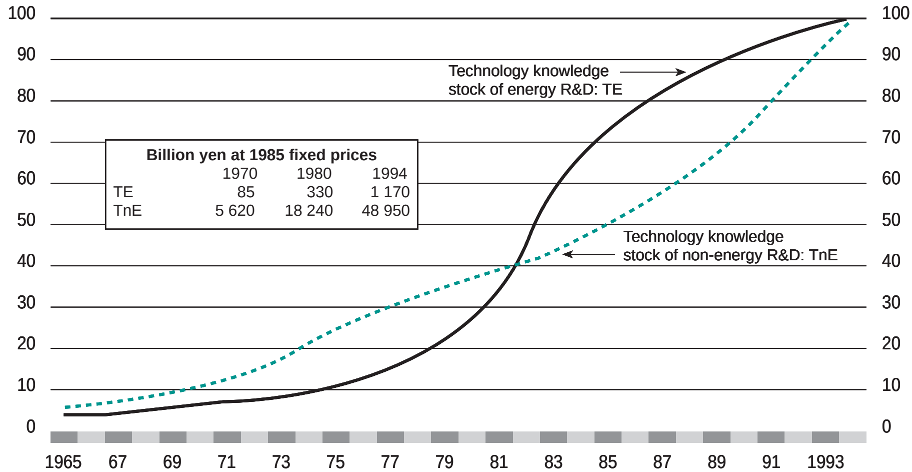
Chart 1. **Trends in factors and their magnitude contributing to change in $CO_2$ emissions in the Japanese manufacturing industry (1970-94)**




*Source:* Author.

| Period | $CO_2$ emissions | Fuel-switching | Energy efficiency | Change in ind. struct. | GDP growth | Miscellaneous |
|---|---|---|---|---|---|---|
| | $\frac{ECO_2}{CO_2}$ | $\frac{EC/E}{C/E}$ | $\frac{EE/Y}{E/Y}$ | $\frac{-EV/Y}{V/Y}$ | $\frac{EV}{V}$ | $\phi$ |
| 1970-73 | 7.12 | –2.19 | –0.20 | –1.10 | 11.00 | –0.39 |
| 1974-78 | –2.29 | –0.24 | –3.98 | –0.32 | 2.31 | –0.06 |
| 1979-82 | –4.11 | –1.09 | –6.31 | –2.93 | 6.34 | –0.12 |
| 1983-86 | 0.11 | 1.28 | –5.00 | –0.13 | 4.27 | –0.31 |
| 1987-90 | 2.60 | –0.72 | –2.66 | –1.83 | 8.04 | –0.23 |
| 1991-94 | 0.52 | –0.15 | 1.10 | –0.13 | –0.24 | –0.06 |
| 1974-94 | –0.71 | –0.19<br>(4.0%) | –3.40<br>(71.3%) | –1.03<br>(21.6%) | 4.06 | –0.15<br>(3.1%) |

Chart 2. **Trends in technology knowledge stock of energy R&D and non-energy R&D in the Japanese manufacturing industry (1965-94)**



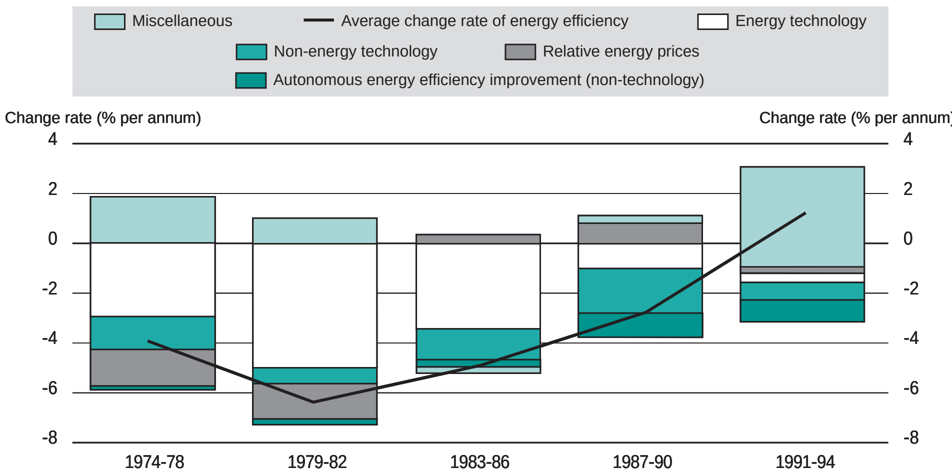

*Source:* Author.

*Note:* Technology knowledge stock is measured by the following equations:

$T_t = R_{t\text{-}mt} + (1 - \sigma_t)T_{t\text{-}1}$, $\sigma_t = \sigma(T_t)$, $m_t = m(\sigma_t)$

where $T_t$ : technology knowledge stock in the period t, $R_t$: R&D expenditure in the period t, $m_t$: time lag of R&D to commercialisation in the period t, and $\sigma_t$: rate of obsolescence of technology in the period t.

Chart 3. **Factors contributing to change in energy efficiency in the Japanese manufacturing industry (1974-94)**




*Source:* Author.

*Note:* Magnitude of contribution is measured by the following equation:

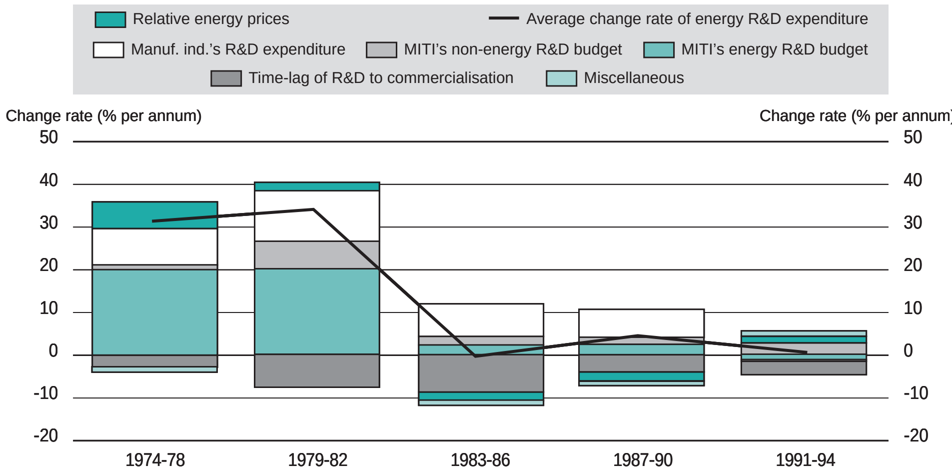
$$\frac{E)E/Y^*}{(E/Y)} > \Big( \frac{\bullet Y}{\bullet X} + \frac{X}{Y} + \frac{E)E/X^*}{E/X} \Big) X > L, K, M^*$$

$\ln E/X = a + b_1 \ln (P_x/P_e) + b_{21} \ln TE + b_{22} \ln TnE + b_3 \mu' t$

where $P_x$, $P_e$: prices of X and energy; TE, TnE: technology knowledge stock of energy R&D and non-energy R&D; $\mu'$: autonomous energy efficiency improvement (non-technology driven); and t: time trend.

| Period | EE/Y / E/Y | Contribution factors | | | | |
|---|---|---|---|---|---|---|
| | | $P_x/P_e$ | TE | TnE | μ | ϕ |
| 1974-78 | –3.98 | –1.53 | –2.90 | –1.34 | –0.17 | 1.96 |
| 1979-82 | –6.31 | –1.39 | –4.96 | –0.74 | –0.25 | 1.03 |
| 1983-86 | –5.00 | 0.33 | –3.46 | –1.23 | –0.36 | –0.28 |
| 1987-90 | –2.66 | 0.85 | –0.99 | –1.69 | –1.10 | 0.27 |
| 1991-94 | 1.10 | 0.20 | –0.38 | –0.71 | –0.94 | 2.93 |
| 1974-94 | –3.40 | –0.37 (8.0%) | –2.56 (55.4%) | –1.15 (24.9%) | –0.54 (11.7%) | 1.22 |

Chart 4. **Factors contributing to change in energy R&D expenditure in the Japanese manufacturing industry (1974-94)**




*Source:* Author.

*Note:* Magnitude of contribution is measured by the following equation:

$$\ln ERD = -6.57 + 0.65 \ln MERD + 0.27 \ln (MnERD) + 0.74 \ln RD + 0.64 \ln Me + 0.25\, Pet$$
$$\quad (6.81) \qquad (3.54) \qquad (3.32) \qquad (4.10) \qquad (2.26)$$

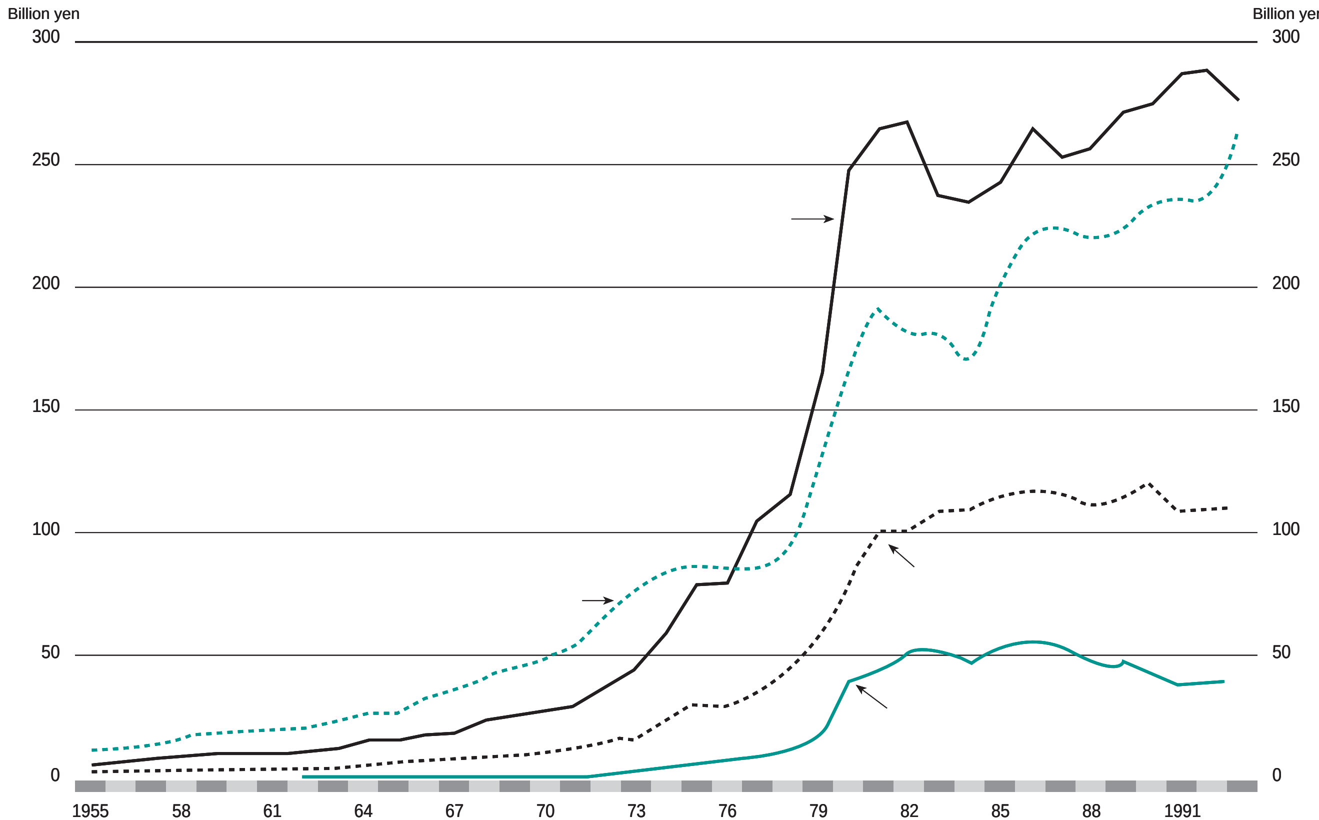
adj. $R2$ 0.993 DW 2.07

where ERD and RD: manufacturing industry's energy R&D and total R&D expenditure; MERD and MnERD: MITI's energy R&D and non-energy R&D budget; Me: time lag of energy R&D to commercialisation; and Pet: relative energy prices with respect to capital prices of technology.

| Period | Industry energy R&D | MITI energy R&D | MITI non-energy R&D | Industry total R&D | Time lag of R&D to commerc. | Relative energy prices | Miscellaneous |
|---|---|---|---|---|---|---|---|
| | $\frac{\Delta ERD}{ERD}$ | $\frac{E\Delta MERD}{MERD}$ | $\frac{E\Delta MnERD}{MnERD}$ | $\frac{\Delta RD}{RD}$ | $\frac{E\Delta Me}{Me}$ | $\frac{E\Delta Pet}{Pet}$ | $\phi$ |
| 1974-78 | 31.77 | 20.33 | 1.08 | 8.19 | –3.01 | 6.44 | –1.26 |
| 1979-82 | 32.99 | 20.64 | 6.22 | 11.36 | –7.34 | 2.25 | –0.14 |
| 1983-86 | –0.09 | 2.37 | 2.15 | 7.73 | –8.70 | –2.29 | –1.35 |
| 1987-90 | 3.46 | 1.78 | 1.03 | 7.88 | –4.25 | –2.04 | –0.94 |
| 1991-94 | 0.35 | –1.08 | 2.32 | –0.50 | –3.39 | 1.33 | 1.67 |
| 1974-94 | 14.56 | 9.36 | 2.49 | 6.99 | –5.23 | 1.39 | –0.44 |

Chart 5. **Trends in energy R&D expenditure by MITI and Japan's manufacturing industry (1955-94)**

1985 fixed prices (billion yen)

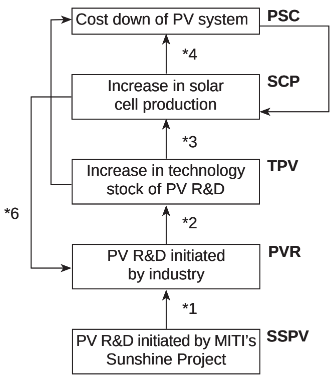



*Source:* Author.

**Inducing impacts of MITI's energy R&D on energy R&D initiated by the Japanese manufacturing industry (1977-94)**

| | Relative energy price | adj. R2 | DW |
|---|---|---|---|
| 1. R&D on energy conservation (CONSV) vs MITI's Moonlight (ML) and non-energy R&D (MITInERD) | | | |
| ln(CONSV) = 3.149 + 0.437 ln(LAG2(ML)) + 0.285 ln(LAG1(MITInERD)) + 0.003 ln(Pey) + 0.411D | | 0.950 | 1.57 |
| (6.41) (2.09) (0.02) (4.58) | 1979-81 = 1 | | |
| 2. R&D on solar energy (SOLAR) vs MITI's solar energy R&D (SS) | | | |
| ln(SOLAR) = 0.981 + 0.871 ln(LAG1(SS) + 0.011 ln(Pey) + 0.285D | | 0.936 | 1.17 |
| (13.62) (0.05) (2.48) | 1979, 80 = 1 | | |
| 3. R&D on coal energy (COAL) vs MITI's coal coversion (SC) and coal combustion (MC) | | | |
| ln(COAL) = –0.584 + 0.289 ln(LAG2(SC)) + 0.845 ln(LAG1(MC)) + 0.509 ln(Pey) + 1.630D | | 0.947 | 2.39 |
| (6.91) (3.12) (1.10) (5.60) | 1980 = 1 | | |
| 4. R&D on oil and gas (OILGAS) vs MITI's oil and gas R&D (MOG) | | | |
| ln(OILGAS) = 0.998 + 0.858 ln(LAG1(MOG)) + 1.362 ln(Pey) + 0.721D | | 0.898 | 1.92 |
| (11.11) (6.31) (5.36) | 1979, 80 = 1 | | |
| 5. R&D on nuclear energy (NUCLEAR) vs MITI's nuclear energy R&D (MN) | | | |
| ln(NUCLEAR) = 3.990 + 0.425 ln(LAG2(MN) + 0.022 ln(Pey) – 0.192D | | 0.896 | 1.93 |
| (8.98) (0.17) (–2.38) | 1979, 80 = 1 | | |
| 6. R&D on electric power (ELECTRIC) vs MITI's electric power R&D (MEP) | | | |
| ln(ELECTRIC) = –1.882 + 1.413 ln(LAG1(MEP) + 0.865 ln(Pey) + 1.431D | | 0.868 | 2.05 |
| (10.49) (1.55) (3.95) | 1979, 80 = 1 | | |

## Chart 6. **MITI's initiative in constructing virtuous cycle for PV development in Japan (1976-94)**




| Equation | Adj.R2 | DW |
|---|---|---|
| *1 $\log(PVR) = 0.30 + 1.03 \log(SSPV_{-1})$ <br> (16.47) | 0.938 | 1.48 |
| *2 $TPV_t = PVR_{t-m} + (1-\rho)TPV_{t-l}$   m = 2.8 years, ρ = 20% p.a. | | |
| *3 $\log(SCP) = -3.83 + 1.37 \log(TPV) + 4.73 \log(Pey)$ <br> (27.67) (9.42) | 0.977 | 1.36 |
| *4 $\log(PSC) = 3.85 – 0.14 \log(TPV) – 0.35 \log(SCP)$ <br> (-3.43) (-11.60) | 0.989 | 1.02 |
| *5 $\log(SCP) = 7.44 – 1.94 \log(PSC_{-1}) + 2.17 \log(Pey_{-1})$ <br> (-47.21) (7.95) | 0.993 | 1.15 |
| *6 $\log(PVR) = 3.14 + 0.60 \log(SCP)$ <br> (25.63) | 0.973 | 1.56 |

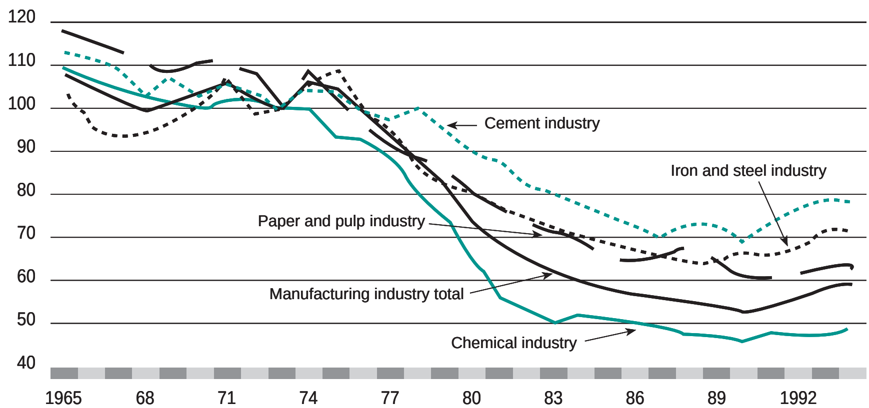
where SSPV: PV R&D budget by the Sunshine Project, PVR: industry's PV R&D expenditure, TVP: technology knowledge stock of PV R&D, SCP: solar cell production, PSC: solar cell production price (fixed price), m: time lag of PV R&D to commercialization, ρ: rate of obsolescence of PV technology, and Pey: relative energy prices.

*Source:* Author.

**Chart 7. Technology spillover from electrical machinery and transportation equipment to iron and steel and chemicals in Japan**

Trend in unit energy consumption in the Japanese manufacturing industry (1965-94)

Index: 1973 = 100




*Source:* Author.

| | | 1980 | 1985 | 1990 | 1994 |
|---|---|---|---|---|---|
| Energy Consumption | Iron and steel | 33.7 | 31.5 | 29.5 | 27.4 |
| | Chemicals | 24.5 | 25.9 | 27.4 | 30.3 |
| | Electrical machinery Transportation equipment | 2.5 | 3.5 | 4.0 | 4.0 |
| | Others | 39.3 | 39.1 | 39.1 | 38.3 |
| | Total | 100 | 100 | 100 | 100 |
| Energy R&D Expenditure | Iron and steel | 10.6 | 11.1 | 6.4 | 4.4 |
| | Chemicals | 4.4 | 5.7 | 2.5 | 2.5 |
| | Electrical machinery | 29.0 | 30.2 | 30.9 | 34.6 |
| | Transportation equipment | 26.6 | 34.4 | 39.4 | 34.2 |
| | Others | 29.4 | 18.6 | 20.8 | 24.3 |
| | Total | 100 | 100 | 100 | 100 |

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