Chapter II
The clean energy technological transformation

Summary

- A global sustainable energy transition needs to be achieved within four decades, a significantly faster rate than in the past.
- Global sustainable energy policy must take into special consideration the 3 billion poor people who aspire to gaining access to electricity and modern energy services.
- The scope of current national and global policies and programmes does not "add up" to the scale of actions needed to meet global emission reduction targets. Paradoxically, they are also overly ambitious in terms of their expected outcomes and are inconsiderate of certain biophysical, techno-economic and socio-political limits to scaling up known technologies. A reality check of current plans is needed so that realistic and well-targeted initiatives can be devised at a far greater scale.
- There is a need for comprehensive, strategic and systemic approaches that emphasize performance goals, niche markets and technology portfolios, especially those related to end-use. In order to take pressure off the technological innovation imperative, individual limits of 70 gigajoules (GJ) primary energy use per capita and 3 tons of carbon dioxide (CO_2) emissions per capita by 2050 may need to be considered. Such energy-use and emissions caps would not affect the development-related aspirations of developing countries.
- The sustainable energy transition offers significant economic opportunities for both developed and emerging market economies, but poses additional development challenges for poorer and more vulnerable countries, which would therefore require enhanced support from the international community.

Introduction

Energy technologies[1] have been greatly shaping society and the environment for the past two centuries. In fact, modern civilizations are largely dependent on fossil fuel energy technologies, which make high-density urban settlements possible. While technological progress has eliminated many problems, it has also added new and often unexpected ones (Grübler, 1998; Diamond, 2005). Emissions of greenhouse gases (GHGs) arising from the combustion of fossil fuels have been the main cause of anthropogenic global warming. All energy technologies, whether they are fossil-based or not, consume resources, use land and

1 For the purpose of the present chapter, energy technology shall comprise not only material inputs and equipment, but also software (that is, explicit and tacit knowledge and human skills) and "orgware" (that is, institutions, regulations and cultural norms) (Dobrov, 1979).

pollute air, water and the atmosphere. Energy use has reached a scale at which planetary boundaries are being breached for a range of essential Earth-system processes, including in terms of global warming and biodiversity loss, which is likely to lead to catastrophic environmental change (Rockström and others, 2009).

The declared goal of establishing a renewable and low-carbon energy system on a global scale remains elusive

Despite two decades of climate change policies; thousands of programmes, initiatives, regulations, market-based instruments and international agreements; and the disbursement of hundreds of billions of dollars in subsidies, funds, research and development (R&D) efforts and development aid, the declared goal of establishing a renewable low-carbon energy system on a global scale remains elusive. In 2005, fossil fuels accounted for 85 per cent of the global primary energy mix, while low-carbon nuclear power accounted for 6 per cent, hydroelectricity for 3 per cent and biomass for 4 per cent. Modern renewables jointly accounted for less than 1 per cent.

New fossil fuel-based plants will remain operational for decades

Global CO_2 emissions have increased at an annual rate of more than 3 per cent, considerably faster than in previous decades (van Vuuren and Riahi, 2008). The past decade was the first in two centuries with increasing CO_2 emissions intensities, owing to a "coal revival", in contrast with the rapid conversion to natural gas in the 1990s. In 2010, the global share of coal reached an estimated 29 per cent, which in relative terms was higher than, and in absolute terms about twice as large as, at the time of the first oil crisis, in 1973. In the 2000s, China alone added more coal power capacity *each year* than the total installed capacity in the United Kingdom of Great Britain and Northern Ireland (International Energy Agency, 2010b, p. 202). These trends, which are diametrically opposed to declared greenhouse gas mitigation goals and targets, are by no means limited to emerging economies. Even in Germany, a country with one of the most ambitious Government goals for greenhouse gas mitigation, 10 coal power plants were under construction and another 12 coal power plants were in the pipeline (Bundesnetzagentur, 2009). These fossil-fuel-based capacities will remain operational for decades and make greenhouse gas reduction efforts increasingly difficult.

In contrast with the actual trend of ever more rapid increases in greenhouse gas emissions, *global* emissions would need to be *reduced* by 50-80 per cent by 2050 and turn *negative* in the second half of this century, in order to stabilize CO_2 concentrations at about 450 parts per million by volume (ppmv), a target recommended by the Intergovernmental Panel on Climate Change (IPCC) and agreed upon at the sixteenth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change,[2] held in Cancun, Mexico, from 29 November to 10 December 2010. Essentially, this would require making the power and transport sector carbon-free *worldwide* by mid-century, in view of the limitations associated with replacing industrial processes based on fossil fuels. Today's CO_2 emitting devices and infrastructures alone imply cumulative emissions of about 496 gigatons (Gt) of CO_2 from 2010 and 2060, leading to atmospheric concentrations of about 430 ppmv (Davis, Caldeira and Matthews, 2010). In other words, even an immediate *global stop* to building new fossil-fired capacities would lead close to the envisaged global target of 450 ppmv by mid-century. This puts into perspective the enormous ambition of the global target, given the long-lived capital stock and rapidly rising energy demand.

Forty per cent of humanity, or 2.7 billion people, continues to rely on traditional biomass, such as wood, dung and charcoal

At the same time, about 40 per cent of humanity, or 2.7 billion people, continues to rely on traditional biomass, such as wood, dung and charcoal. Air pollution from inefficient stoves leads to an estimated 1.5 million premature deaths per year, more than from malaria, tuberculosis or HIV. About one fifth of humanity or 1.4 billion people,

2 United Nations, *Treaty Series*, vol. 1771, No. 30822.

continues to live without access to electricity, mainly in South Asia and sub-Saharan Africa (International Energy Agency, United Nations Development Programme and United Nations Industrial Development Organization, 2010). Many more, especially in urban areas, have access but cannot afford to make full use of it. The United Nations Secretary-General's Advisory Group on Energy and Climate Change proposed the goal of universal access to modern energy services by 2030 (United Nations, 2010a). It is important to note that bringing universal access to modern energy services to almost 3 billion people would require only about 3 per cent higher electricity generation, less than 1 per cent more demand for oil and less than 1 per cent more CO_2 by 2030 (International Energy Agency, United Nations Development Programme and United Nations Industrial Development Organization, 2010). Thus, the development aspirations of the world's poor are not in conflict with efforts to solve the climate problem. The 500 million richest people, who constitute only 7 per cent of the world population, are responsible for half of all greenhouse emissions. They live in every country of the world and earn more than the average citizen of the United States of America. In contrast, the poorest 3.1 billion people are responsible for only 5-10 per cent of the total (Pacala, 2007; Chakravarty and others, 2009).

The global energy challenge is immense, as evidenced by the multiple global objectives explored by the Global Energy Assessment (GEA) (Riahi and others, forthcoming): (a) to ensure universal access to electricity and modern cooking fuels by 2030; (b) to reduce premature deaths due to air pollution by 50 per cent by 2030; (c) to limit global average temperature change to 2° C above pre-industrial levels by 2100 (with a probability of greater than 50 per cent); and (d) to establish energy security, for example, to limit energy trading and increase diversity and resilience of energy supply by 2050. Meeting GEA objectives requires a complete transformation of the global energy technology system in the course of one generation, which is a considerably shorter time-frame than was the case for historical energy transitions. Governments have called for concerted actions to accelerate technology change towards cleaner energy technology. Many technology optimists believe such acceleration is essential and have in this regard coined the term "energy technology innovation imperative" (Holdren, 2006). Innovation in this context encompasses the full spectrum ranging from incremental improvements to radical breakthroughs and from technologies and infrastructure to social institutions and individual behaviours (Wilson and Grübler, 2010).

Several Asian Governments are pursuing energy technology-focused industrial policies, with mostly positive developmental benefits

Simplistic solutions dominate present national and global debates on how to meet the energy technology innovation imperative. Technology optimists suggest "big push" policies to scale up available technologies. Others focus on market incentives and hope that the necessary technological transformation will come about by "getting prices right" through internalizing environmental externalities. Several Governments in Asia are pursuing energy technology-focused industrial policies, with mostly positive developmental benefits. However, evidence suggests that none of these approaches has the potential to sufficiently accelerate energy technology change on the required global scales. Indeed, most Government energy technology programmes and private sector projects have not met their overambitious goals in recent decades. Reality checks are needed to enable Governments to devise better policies and programmes at scales commensurate with the challenge. Better-focused and greater efforts to move to cleaner and renewable energy will be needed to ensure climate stabilization while allowing developing countries to satisfy their rapidly increasing demand for commercial energy which is linked to their development aspirations. Historically, such huge challenges were addressed consecutively rather than concurrently.

Global energy technology transitions

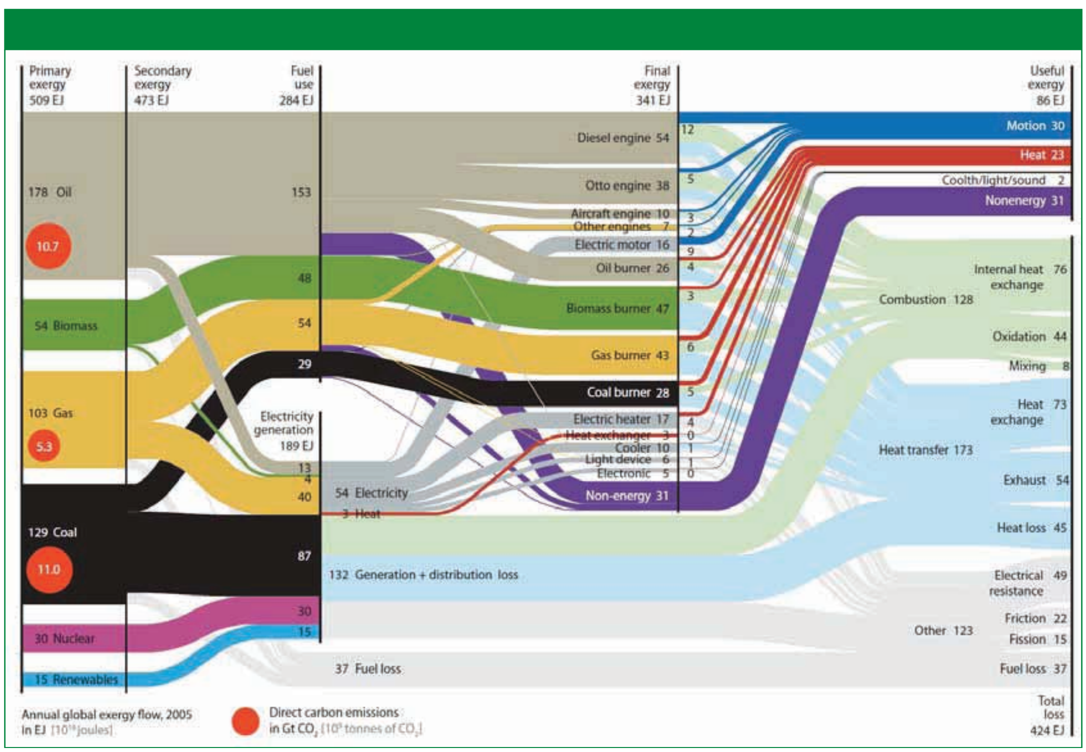
Past energy technology transitions provide lessons for current efforts and can inform future visions of energy technology change in the twenty-first century.[3]

The global energy system

Specific energy technologies should not be analysed in isolation

The global energy system is a planetary-scale complex network of energy converters and energy flows. Figure II.1 illustrates the associated global flows of "exergy", that is, the energy available to be used, at the most aggregate level, from extraction at the primary level through the secondary, final and useful energy levels. It illustrates the dominance of fossil fuels and the low overall efficiency of the global system. It should also be noted that most greenhouse gas mitigation efforts focus on electricity supply, even though most losses are incurred from the final to the useful level. Useful energy is divided into motion (transport and machines), heat (mainly buildings) and non-energy (dominated by six materials). The underlying global reference energy system of interlinked energy technologies is even more complex. As the overall system is more than the sum of its components, for most purposes neither specific energy technologies (such as a wind power plant) nor specific parts of the system (such as renewable energy) should be analysed in isolation.

Figure II.1
Global exergy system flows, 2005



Source: Cullen and Allwood (2009).

3 The present subsection draws upon Wilson and Grübler (2010) and Grübler and others (forthcoming).

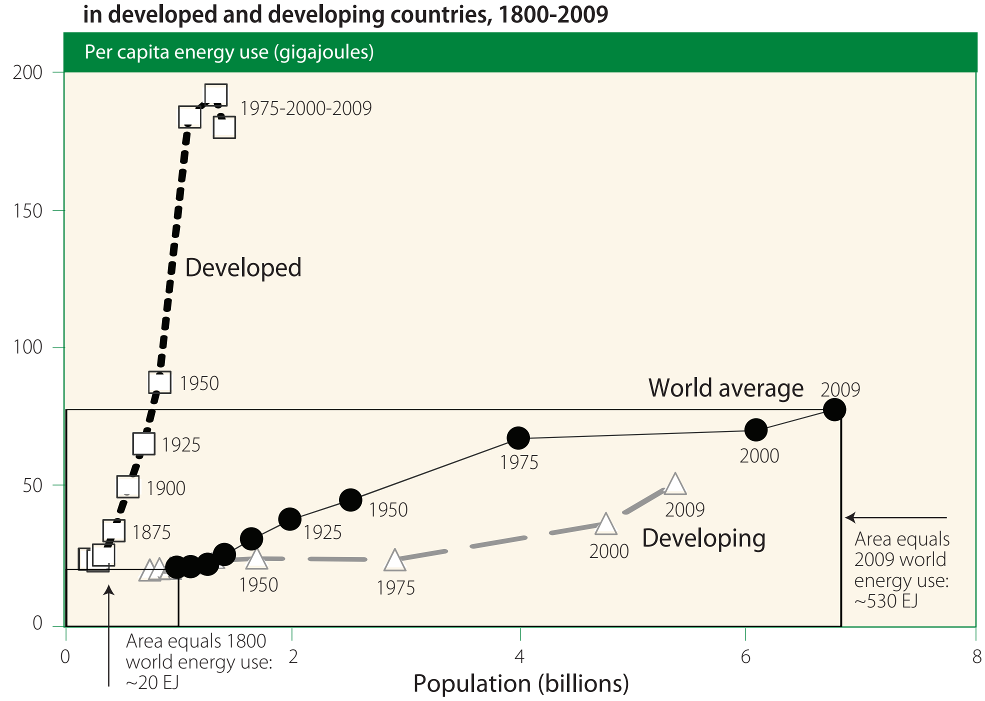
History of global energy transitions

Over the past 200 years, global energy use has grown by a factor of 25-530 exajoules (EJ) in 2009, compared with a sevenfold increase in population, driven by demand for higher-quality energy services made possible by underlying energy technology change. Throughout the twentieth century, total energy use in developed countries had been much higher than in developing countries. In recent decades, however, energy demand in China, India and other emerging economies has grown rapidly, so that by 2009, more than half of primary energy was used in developing countries. This share is expected to continue to increase to at least two thirds over the coming decades. At present, 2.7 billion people continue to rely on traditional, non-commercial fuels typical for pre-industrial societies. They use only between 15 and 50 GJ of primary energy per capita, delivering about 2-5 GJ of per capita in useful energy services. Growth of per capita energy use in developing countries has accelerated since 1975, whereas use in developed countries has stagnated (figure II.2).

There are persisting differences between the development trajectories of countries, spanning the extremes of highly energy-intensive and highly energy-efficient. Initial differences in resource endowments or social configurations can be perpetuated over time by differences in economic activity, technology adoption rates, consumption patterns and infrastructure, which shape the direction of path-dependent energy technology change (Wilson and Grübler, 2010). At 1990 levels of energy conversion efficiency, a minimum level of 40-50 GJ primary energy per capita would be associated with a decent quality of life (Smil, 2004). Cross-country evidence suggests that, typically, no additional human development gains are obtained through primary energy use above 110 GJ per capita at prevailing conversion efficiencies. Improving overall global energy conversion efficiency from the present 11 per cent to 17 per cent would result in provision of the same level of energy services using 70 GJ of primary energy per capita.

Typically, no additional human development gains are obtained with primary energy use above 110 GJ per capita

Figure II.2
Trends in per capita energy use and population in developed and developing countries, 1800-2009



Source: Wilson and Grübler (2010).

Note: Non-commercial energy sources are included. Countries are classified using the United Nations Framework Convention on Climate Change categories as Annex I (developed or industrialized) or non-Annex I (developing) countries. Data are from Grübler (2008) and updated from British Petroleum (2010) and International Energy Agency (2010a). Data prior to 1950 are estimates.

History of global energy technology transitions

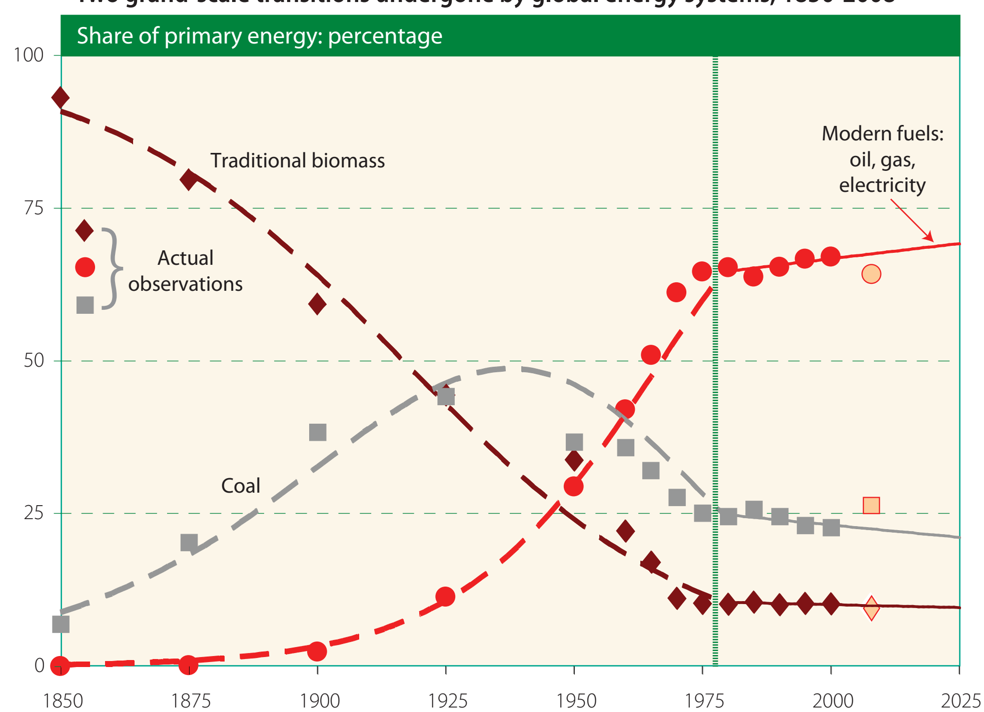
Two major energy technology transitions have shaped the structure of the global energy system and the qualitative dimension of energy use since the onset of the industrial revolution (Nakicenovic, Grübler and McDonald, 1998). The first, associated with the emergence of steam power relying on coal (Landes, 1969), took more than a century to unfold (figure II.3). The second, characterized by the displacement of the coal-based steam technology cluster by electricity and petroleum-based technologies, is only about half-complete, with 2.7 billion people still lacking access to modern energy services (Global Energy Assessment, forthcoming).

There is no evidence of any differences in the speed of energy technology change across a wide range of technologies

These transitions towards higher-quality energy fuels took place through successive substitutions going from traditional fuels to oil, gas and nuclear. At the global level, these substitutions had occurred at intervals of 70-100 years for the 250 years until 1975 (Marchetti and Nakicenovic, 1979). Since 1975, however, this process has slowed to a global transition time of about 250 years, primarily as a result of government interventions and politically induced high and volatile oil prices. In addition, at the level of plants and units, there is no evidence of any differences in the speed of energy technology change across a wide range of technologies since the nineteenth century (Wilson, forthcoming). The historical energy technology transitions have been characterized by a number of stylized patterns (Wilson and Grübler, 2010):

- End-use applications drive supply-side transformations
- Quality/performance dominates cost in the initial market niches
- Energy technologies do not change individually but in clusters, with "spillovers"

Figure II.3
Two grand-scale transitions undergone by global energy systems, 1850-2008



Sources: British Petroleum (2010); Grübler (2008); and International Energy Agency (2010a)

Note: The diamonds, dots and squares are actual data points, including estimated values for 2008. The broken lines are coupled logistic equations fitted on the data over the period 1850-1975.

- Time periods for energy technology change are decades, not years
- Experimentation and learning precede “upscaling” and widespread diffusion
- The size and the rate of expansion of energy conversion capacity are inversely related
- Diffusion in late “adopter” regions is faster than in initial “innovator” regions, but maximum market penetration levels are lower
- Both sufficient time and resources are needed for energy technology learning

Future scenarios

From 1950 to 1990, energy-related global greenhouse gas emissions increased by about 3 per cent per year, mainly owing to increases in population (+1.8 per cent) and incomes (+1.9 per cent), the effect of which was moderated by lower energy intensity consumption patterns (-0.3 per cent) and better, lower-carbon technologies (-0.4 per cent) (Waggoner and Ausubel, 2002). Policy has typically focused on technology as the main lever for reducing emissions and it is indeed a powerful driver. Future energy technology change will be as important for determining future greenhouse gas emissions levels as long-term demographic and economic developments over the course of the twenty-first century (Roehrl and Riahi, 2000). Alternative technology strategies result in a divergence of emissions levels only gradually, after several decades or more, owing to the long lifetimes of power plants, refineries, buildings and energy infrastructure (Grübler, 2004); but near-term technology and policy decisions will have sown the seeds of subsequent divergences, translating into different environmental outcomes as new technologies gradually replace older ones.

Claims that “the technology exists to solve the climate problem” underestimate the scale of efforts required

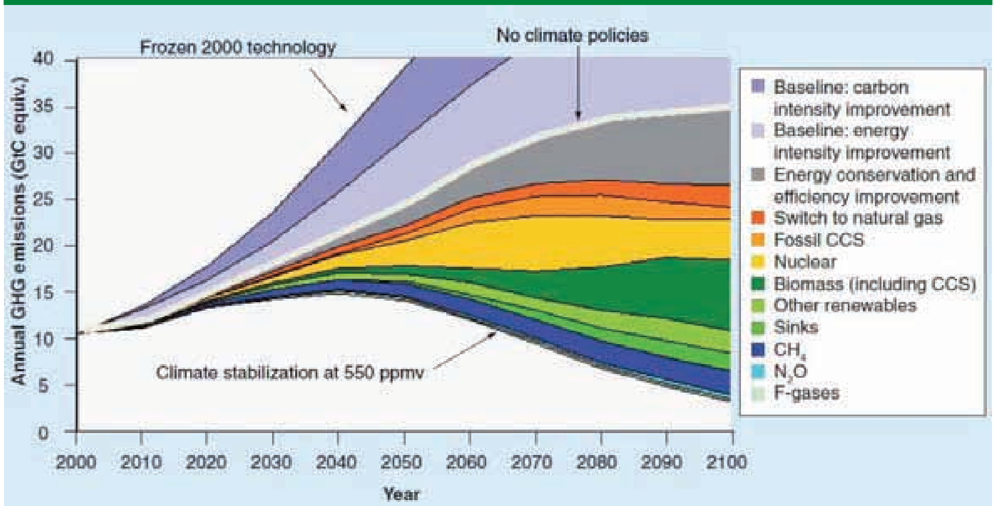
Scenario analysis has helped to identify robust energy technology portfolios across a wide range of assumptions with respect to energy demand, resource constraints and availability and cost of technologies, and the extent of greenhouse gas constraints (Roehrl and Riahi, 2000; Riahi, Grübler and Nakicenovic, 2007; Grübler and Riahi, 2010). Figure II.4 illustrates the contributions of energy technologies to greenhouse gas emissions reductions, under a high-emissions baseline scenario, required for stabilization at a concentration of 550 ppmv CO_2e by 2100. The top two “mitigation wedges” show the contributions (in annual gigatons of carbon (GtC)) of (supply-side) carbon intensity improvements and (demand-side) energy intensity improvements in the baseline relative to a “frozen” state of technological development in 2000. This difference illustrates the innovation challenge of incremental energy efficiency improvements. Popular claims that “the technology exists to solve the climate problem” reflect the idea that no necessarily disruptive revolutionary changes (for instance, to nuclear fusion) would be needed, but such beliefs underestimate the challenge of achieving continued incremental improvements in line with historical trends.

The ranking of these mitigation wedges is quite robust across scenarios, with energy conservation and efficiency accounting for more than half the emissions reductions. Indeed, across the wide range of scenarios, energy efficiency contributed about 59 per cent of the cumulative greenhouse gas emissions reductions from 2000 to 2100, compared with the much lower contributions of renewables (18 per cent), nuclear (9 per cent), fossil fuels (6 per cent) and other means (8 per cent) (Riahi, Grübler and Nakicenovic, 2007).

Several global scenarios have explored feasible levels of lower per capita energy use and low greenhouse gas emissions that do not compromise economic development. For

Figure II.4
"Robust" climate change mitigation wedges, 2000-2100

Share of primary energy: percentage



Source: Riahi, Grübler and Nakicenovic (2007)

Abbreviations: CCS, carbon capture and storage; CH_4, methane; N_2O, nitrous oxide; F-gases, fluorinated gases.

example, the GEA efficiency scenario shows that the world's average primary energy use per capita can decrease from 71 to 63 GJ from 2010 to 2050, with average per capita gross domestic product (GDP) still tripling (in constant dollar terms). This implies an improvement in eco-efficiency by a factor of 3.2, which is almost as ambitious as the "factor 4" goal of doubling wealth and halving resource use, originally suggested by von Weizsäcker, Lovins and Lovins (1998). Thus, even world average levels of energy use of less than 70 GJ per capita would be achievable by mid-century, in line with the target suggested by the present *Survey* (see below).

Efforts to accelerate energy technology change

The pace of the global energy transition has slowed significantly since the 1970s

The pace of the global energy transition has slowed significantly since the 1970s, despite national and international efforts to accelerate energy technology change in response to the oil crises of the 1970s, current concerns about global warming, and the goal of ensuring universal access to modern energy services.

The international energy technology agenda

A complex system of organizations and institutions has emerged at the international level to promote energy technology cooperation and provide both financial resources for clean energy investments and price signals to favour low-carbon energy technologies; and a global system for the transfer of hundreds of billions of United States dollars is in the making.

The International Energy Agency (IEA) maintains 40 multilateral technology initiatives, also known as implementing agreements, covering the full range of energy technologies, including programmes with voluntary participation designed to accelerate the deployment of clean energy technologies and cost-effective technologies for carbon capture and storage (CCS). Thus far, however, these international efforts have had a relatively small effect on the global energy transition.

CDM investments have been concentrated in a handful of large emerging economies, such as China, Brazil and India

The Clean Development Mechanism (CDM) under the Kyoto Protocol to the United Nations Framework Convention on Climate Change,[4] for instance, was expected to greatly stimulate clean energy technology transfer to developing countries and significantly reduce costs for developed countries. The market value of Clean Development Mechanism transactions had reached $6.5 billion in 2008, but dropped thereafter by about 60 per cent as a result of the financial crisis and uncertainty about the future climate policy regime. Looking ahead to 2012, renewable energy projects are estimated to make up 61 per cent of the total number of CDM projects, accounting for 35 per cent of certified emissions reductions (CERs), with industrial gas and methane projects accounting for just under half of the remainder of CERs. If fully implemented, CDM projects contracted during the period 2002-2008 would require $106 billion worth of low-carbon investment, primarily in "clean" energy (Kossoy and Ambrosi, 2010). CDM investments have been concentrated, however, in a handful of large emerging economies, such as China, Brazil and India.

From 1991 to 2009, the Global Environment Facility (GEF), which serves as a financial mechanism for the United Nations Framework Convention on Climate Change, allocated more than $2.7 billion to climate mitigation activities while leveraging an additional $17 billion in financing. In 2008, the World Bank also established the Climate Investment Funds which represent a collaborative effort among the multilateral development banks to address climate finance gaps. By 2010, contributors had pledged $6.4 billion in new funds. One component, the Clean Technology Fund finances the scaling up of demonstration, deployment and transfer of clean technologies and focuses on countries with significant mitigation potential. The first round of investment plans encompasses 13 countries, energy efficiency projects, bus rapid transit, concentrating solar power, and wind power.

The need to transfer environmentally sound technologies is recognized under the United Nations Framework Convention on Climate Change

The transfer of environmentally sound technologies is recognized under the United Nations Framework Convention on Climate Change, but action on the ground has progressed relatively slowly. The Conference of the Parties at its sixteenth session, agreed to establish a Climate Technology Centre and Network, which aim to support technology transfer and local technology innovation capacity.

National plans for clean energy technology

Efforts of emerging and other developing economies to support clean energy technology have typically focused on the creation of domestic manufacturing and export capacities

Recent efforts in developed economies to support clean energy technology have typically focused on economic instruments for creating niche markets and promoting the commercial diffusion of new technologies. Efforts of emerging and other developing economies to support clean energy technology have typically focused on domestic research, development, manufacturing and export capacities. China's Twelfth Five-Year Plan, endorsed in March 2011, encompasses a green growth strategy geared towards building technology leadership, through special efforts to develop and deploy wind, solar, hydro, nuclear, energy efficiency, electric cars, "smart grids", infrastructure and high-speed rail. It includes a plan to install 10 million charging stations for electric cars and to increase installed renewable energy capacity by 47 per cent by 2020. It plans to invest €57 billion in new ultra high voltage (UHV) transmission lines by 2015, and €460 billion to develop smart grids, and to increase nuclear power capacity from 10 to 50 GW, although most investments will continue to be for "clean" coal. South Africa aims to slow its greenhouse gas emissions growth and reduce those emissions after 2030, through increased energy efficiency,

4 United Nations, *Treaty Series*, vol. 2303, No. 30822.

feed-in tariffs for renewables, development of carbon capture and storage for coal-fired power plants and coal-to-liquid plants, a levy on coal-fired power and the introduction of a carbon tax. The Republic of Korea is implementing a green growth strategy and five-year action plan which aim for a 46 per cent reduction in energy intensity by 2030 and for an 11 per cent share of renewable energy. The national energy plan for 2008-2030 foresees investments in low-carbon transport, hybrid vehicles, renewable energy technologies and the construction of 10 nuclear power plants. Mexico has set an indicative reduction target for its greenhouse gas emissions by 50 per cent from 2000 to 2050, and its Special Climate Change Programme makes provisions for wind power, cogeneration, efficient household appliances and lighting, promoting rail freight, and 600,000 efficient cooking stoves.

Energy plans of the poorest and most vulnerable economies have aimed to find a balance between Governments' immediate priorities and the priorities of aid donors, in order to leverage development assistance. For example, energy plans and policies of a number of small island development States aim to address their special vulnerabilities and promote renewable energy. For example, Maldives announced its goal of achieving a carbon-neutral energy sector by 2020; Tuvalu aims to achieve 100 per cent renewable energy utilization by 2020; there have been positive experiences with thermal solar water heating in Barbados, Mauritius and Palau; hybrid solar-diesel power generation is being piloted in Maldives and Tuvalu; and geothermal energy is in the early phases of exploration in Saint Kitts and Nevis and Saint Lucia. Despite such commitments, however, fossil-fuel use has continued to increase faster than renewable-energy use in most small island development States (United Nations, 2010a).

National plans for universal access to modern fuels and electricity

Globally, less than 65 per cent of the rural population had access to electricity in 2008

Globally, less than 65 per cent of the rural population had access to electricity in 2008 (International Energy Agency, 2009). Two thirds of the people without electricity access were in sub-Saharan Africa and South Asia. Only 11 per cent of the rural population in sub-Saharan Africa have access to electricity. From 1970 to 1990, more than 1 billion people had gained electricity access, half of whom were in China alone. From 1990 to 2008, almost 2 billion additional people secured electricity access (Global Energy Assessment, forthcoming). However, there is no evidence for acceleration or deceleration of electrification over the past 100 years. Historically, the process of electrification has taken several decades in all countries. The United Kingdom and the United States needed about 50 years to achieve universal access around 1950. Among the emerging economies, Mexico, China, Brazil, Thailand and Mauritius achieved universal access in the 1990s. India and South Africa, however, still have some way to go, as do all least developed countries. The time needed to achieve universal access to electricity has ranged from about 20 years in Thailand and 40 years in China to 90 years in Mexico. Countries with low population densities or those consisting of dispersed islands face special challenges. Electrification in remote islands remains limited owing to high capital costs, despite special efforts made by small island developing States. For example, Fiji completed about 900 rural electrification community projects between 2005 and 2009, in order to be able to reach universal electricity access by 2016 (United Nations, General Assembly, 2010b).

The benefits of electrification are clear. For poor households in developing countries, having household lighting has been estimated to add between $5 and $16 per month in income gains. The added benefits of access to electricity in general would be in the order of $20-$30 per household per month through enhanced entertainment, time savings, education and home productivity (World Bank, Independent Evaluation Group, 2008). These benefits outweigh by far the $2-$5 per month that poor households typically pay for the cost of electricity.

For poor households in developing countries, household lighting adds between $5 and $16 per month in income gains

Energy efficiencies of kerosene, candles and batteries for lighting are very low. As a result, lighting services with kerosene cost as much as $3 per kilowatt-hour (kWh), which is higher than the cost of lighting with solar electricity, at about $2.2 per kWh in poor countries. In poor countries, diesel generators and micro-utilities typically provide lighting at a cost of $0.5-$1.5 per kWh, compared with centralized traditional utilities which often provide lighting at an effective cost of less than $0.3 per kWh. However, for traditional utilities, providing services to poor households becomes economically interesting only at demand levels of higher than 25 kWh per month, whereas poor households already derive great benefits per unit of cost in the range of 1 to 4 kWh per month.

For the poorest people in developing countries, cooking (and space heating in cold climates) can account for 90 per cent or more of the total volume of energy consumed (World Energy Council and Food and Agriculture Organization of the United Nations, 1999). Relatively simple and inexpensive improved stoves can reduce by as much as 30 per cent the amount of fuel needed for cooking (Global Energy Assessment, forthcoming). Some of these cooking stove programmes, including their costs, are described below.

Relatively simple and inexpensive improved stoves can reduce by as much as 30 per cent the amount of fuel needed for cooking by the poorest people in developing countries

National energy technology innovation strategies

An increasing number of Governments—notably, those of China, Japan and the Republic of Korea—and the European Union (EU) have adopted or followed some kind of national energy technology innovation strategy. Such strategies are typically part of national innovation systems, as discussed in chapter V, and provide a framework for coherent packages of policies and programmes that encompass all stages of the technology life cycle. The EU Lisbon Strategy provides a broad framework for a set of research, development and demonstration (RD&D) framework programmes. The fact that Japan has long focused on the promotion of performance targets for specific technologies has made the country the world leader in energy efficiency. China and the Republic of Korea have implemented industrial policies that focus on rapid adoption, local research, and manufacturing and deployment capacity, supported by flexible financial and regulatory support to accelerate qualitative improvements.

In China, energy technology R&D has expanded rapidly and is dominated largely by Government-owned enterprises which provide 85 per cent of all energy-related R&D. Similar to those of Organization for Economic Cooperation and Development (OECD) member countries, the energy R&D portfolio is dominated by supply-side options, of which more than half entailed fossil fuel-related technologies and 30 per cent, electric power, transport and distribution. Most recently, the Government has strengthened its patent system, with the number of filings having boomed since 2002, which will soon make China's patent office the world's largest. The wind power sector offers a good example of China's rapid creation of local capacities. The market share (of *cumulative* installed wind power capacity) of foreign manufacturers in China declined from 75 per cent in 2004 to 38 per cent in 2008, while the share of domestic manufacturers increased from

China's patent office will soon be the world's largest

23 to 59 per cent.[5] Such rapid replacement of firms' market position has been unheard of in other countries' energy markets (see chap. V).

Investments in research, development and demonstration (RD&D), market formation, and diffusion

Table II.1 provides global estimates of public and private investments in energy innovation, market formation, and diffusion (Wilson and Grübler, 2010; Grübler and others, forthcoming). In 2010, investments in commercial diffusion amounted to between $1 trillion and $5 trillion, substantially more than the $150 billion-$180 billion invested in market formation and the $50 billion for RD&D. RD&D and Government-driven market formation investments focused on power and fuel supply, whereas the majority of private sector diffusion investments were for end-use and efficiency.

Table II.1
Global estimates of public and private investments in energy innovation, market formation, and diffusion, 2010

Billions of 2005 United States dollars

	Innovation RD&D	*Market formation*	*Diffusion*
End-use and efficiency	>>8	5	300-5,000
Fossil fuel supply	>12	>>2	200-550
Nuclear	>10	0	3-8
Renewables	>12	~20-60[a]	>20
Electricity generation, transmission and distribution	>>1	~100	450-520
Other[b] and unspecified	>>4	<15	..
Total	**>50**	**<150-180**	**1,000-5,000**

Sources: Grübler and others (forthcoming); and International Energy Agency (2010b).
a The high estimate is from International Energy Agency (2010b).
b Hydrogen, fuel cells, other power and storage technologies, and basic energy research.

Investment in research, development and demonstration (RD&D)

Today's level of public spending for energy-related research and development in developed countries is still well below that of the 1970s and early 1980s

Only one fifth of the $50 billion in public and private RD&D investments was for end-use technologies and energy efficiency in 2010. The R&D intensity of the energy supply industry was comparable with that of the textile industry, but much lower than that of manufacturing. Public investment in energy-related RD&D continues to be low in developed countries, amounting to 5 per cent of total public RD&D. It had increased rapidly in response to the oil crises of the 1970s, but collapsed in the mid-1980s in line with falling oil prices and privatization, only to recover from 2000 in response to concerns about global warming. Today's level of public spending for energy-related RD&D in developed countries is still well below that of the 1970s and early 1980s, even though overall (not just energy) RD&D budgets have doubled since the 1980s (Nemet and Kammen, 2007). Public spending on RD&D of nuclear, fusion, fossil fuels and renewable energy technologies is lower in each case than in 1980.

5 Data from Tan and others (2010).

Over the past 20 years, emerging economies have become leaders in terms of public RD&D expenditures. They are also emerging as leaders in terms of renewable energy patents. Energy RD&D in Brazil, the Russian Federation, India, Mexico, China and South Africa was about $19 billion (in PPP terms), which is more than the total public energy RD&D budget of all IEA countries combined (estimated at $12.7 billion in PPP terms). This challenges the conventional wisdom that new energy technologies are developed in OECD countries and transferred to developing countries. Energy RD&D investments in emerging economies were focused on fossil fuel and nuclear energy, with renewables and energy efficiency underrepresented (table II.2).

Table II.2
Public and private spending on energy-related RD&D in selected emerging economies and the United States of America, 2004-2008[a]

Millions of 2008 United States dollars at PPP

	Fossil (including CCS)	*Nuclear (including fusion)*	*Electricity, transmission, distribution and storage*	*Renewable energy sources*	*Energy efficiency*	*Energy technologies (unspecified)*	***Total***
China	7 044	19	..	..	161	5 885	**14 772**
Brazil	1 246	8[b]	122[b]	46[b]	46[b]	196	**1 664**
Russian Federation	430	..	22[b]	14[b]	25[b]	553	**1 045**
India	800	965[b]	35[b]	57[b]	..	..	**1 857**
Mexico	140	32[b]	79[b]	..	263[c]	19[c]	**534**
South Africa	164	164	26[c]	7[c]	..	9[b]	**370**
Subtotal	**9 624**	**>1 187**	**>285**	**>124**	**>497**	**>6 662**	**>18 580**
United States	1 821	804	319[b]	699[b]	525[b]	2 510	**6 678**

Source: Gallagher and others (forthcoming).
a Most recent year available.
b Government only.
c Private sector only.

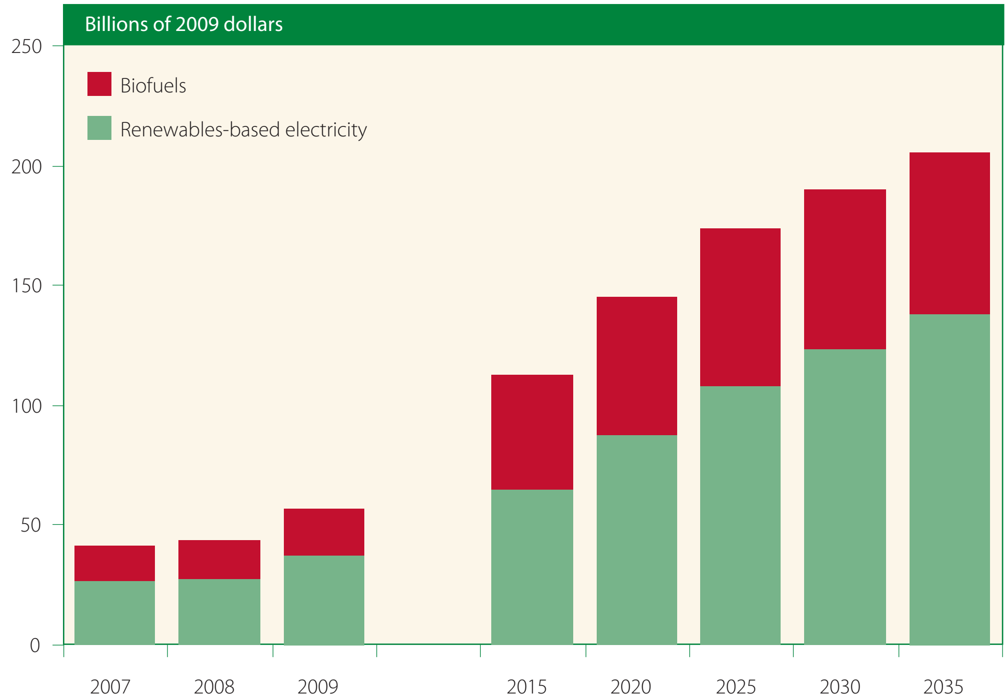
Investment in market formation

Market-formation interventions include public and private investments in the early stages of technological diffusion and public procurement

Market-formation investments, which include public and private investments in the early stages of technological diffusion, are sometimes also referred to as "niche market" investments. These include public procurement and government subsidies for certain technologies, as well as private investments involving renewable performance standards, carbon taxes and feed-in tariffs (chap. V). About $100 billion out of the total of $150 billion-$180 billion in global investments for market formation was for electricity generation, transmission and distribution, $20 billion-$60 billion for renewables and about $5 billion for end-use and efficiency. The niche market investments for renewables are expected to increase rapidly in the coming years, in view of current Government plans in developed and developing countries alike. International Energy Agency (2010b) has estimated that government support for renewables will rise from $57 billion in 2009 to $205 billion in 2035 (figure II.5).[6] By comparison, fossil-fuel consumption subsidies amounted to $312 billion in 2009 (ibid.). These numbers do nonetheless indicate that Governments favour renewables, since, excluding grid investments, Government subsidies for modern renewables amounted to $9.7/GJ compared with $0.8/GJ for fossil fuels.

6 This assumes that world average support per unit will drop from 5.5 cents/kWh in 2009 to 2.3 cents/kWh in 2035, but does not take into account the additional costs of integrating intermittent renewable sources into the network.

Figure II.5
Annual global support for renewables in the IEA New Policies Scenario, 2007-2035



Source: International Energy Agency (2010b).
Note: The IEA New Policies Scenario assumes cautious implementation of recently announced commitments and plans, even if not yet officially adopted.

Investment in diffusion

Global investments in energy and end-use technologies were more than double supply-side investments

Global supply-side energy investment was about $740 billion in 2010, with $70 billion for renewables. These investments were dominated by electricity generation, transmission and distribution (51 per cent) as well as upstream investments in fossil fuel supply (46 per cent), including the oil exploration and production component and the gas exploration and production component which accounted for 19 and 13 per cent, respectively. The most important renewables investments were in large-scale hydropower (annual capacity additions of 25-30 gigawatts (GW)) and biofuels ($20 billion, of which $8 billion was for Brazil's ethanol). Global investment in energy end-use technologies was more than double the supply-side investments, and reached an estimated $1.7 trillion in 2005, of which almost $1.2 trillion was for road vehicles (Grübler and others, forthcoming).

Public-private partnerships in energy investments have become increasingly popular, accounting for almost $40 billion in the first semester of 2009 despite the global financial crisis. Other private sector investments in energy technology include investment by angel investors, companies' internal investments, debt instruments, project finance, mergers and acquisitions, and investments in publicly listed energy technology firms. Energy-related venture capital investments boomed in EU and North America in recent years, reaching $15.5 billion, or 10 per cent of all private investments in energy technology diffusion in 2008 (International Energy Agency, 2009). Most of these investments were for solar, biofuels, biomass, battery technologies, smart metering, software, and high-efficiency engines.

Government energy technology programmes

The following selected examples of government energy technology programmes offer important lessons for future programmes.[7] Most of the programmes have focused on power supply or alternative fuels.

Ethanol in Brazil, the United States and Mauritius

In response to the oil crisis and the erosion of trade preferences for sugar exports, Brazil's military Government launched the world's first large-scale ethanol programme in 1975, with producer subsidies and user incentives aimed at a rapid shift towards dedicated engines running on ethanol. In response to low gasoline prices in the mid-1980s, a national research programme was started which achieved a reduction in production costs from $35/GJ (in 2004 United States dollars) to less than $10/GJ in 2009, mainly through higher yields. In Brazil, ethanol derived from sugar cane has a high energy return of 8.3 times the energy input (ranging from 3.7 to 10) and high yields of about 5,500 litres per hectare. In addition, the introduction of flexible fuel engines (developed with foreign automobile companies) allowed users to choose the desired mix of ethanol and gasoline, thus creating fuel competition and a hedge against lower future oil prices from 2003. The cumulative subsidy aimed at making up for the difference between the higher ethanol production cost and world oil prices between 1975 and 2004 amounted to an estimated $50 billion. Rising oil prices in recent years meant that ethanol production costs became cheaper than world oil prices after 2004. Flexible fuel engines have been highly successful, reaching 81 per cent of the light-vehicle registrations by 2008 (Brazil, Associação Nacional dos Fabricantes de Veículos Automotores, 2008). In this context, it should be noted that, in January 2009, gasoline prices were again lower than ethanol production costs owing to the global recession, but this had again been reversed by January 2011.

In the United States, commercial production of fuel ethanol from corn had started in 1980, reaching 5 billion litres in 1995 and 35 billion litres in 2008. In 2007, the United States Congress passed a bill that mandated the production of 140 billion litres of corn ethanol by 2022, which would be equal to about 13 per cent of United States gasoline demand. If this goal were to be achieved domestically, it would require using the entire United States corn harvest.

In recent years, many developing countries in tropical zones have tried to learn from Brazil's experience with ethanol, and experimented with various local crops. An interesting case is that of Mauritius, which created a local sugar cane and biofuel research institute. While lower sugar cane yields and a smaller scale of operation led to ethanol prices that were about twice as high as those of Brazil, Mauritius has successfully deployed economical bagasse-based cogeneration. It should be noted, however, that, even if all tropical countries attained sugar cane yields as high as Brazil's and all of the world's sugar cane production (19 million hectares in 2005) were shifted to ethanol production, the resulting yield would meet only about 6 per cent of the world's gasoline demand.

Even if all of the world's sugar cane production were shifted to ethanol production, the resulting yield would meet only about 6 per cent of the world's gasoline demand

7 The present subsection draws upon the module on energy technology innovation of the Global Energy Assessment (Grübler and others, forthcoming), which also provides a series of detailed case studies.

Coal-based synthetic fuels in the United States

In response to the second oil crisis, the United States embarked on a large-scale programme to produce synthetic fuels from coal. In 1980, it had established the Synthetic Fuels Corporation which was to improve technologies and produce 2 million barrels of liquid fuel per day by 1992, at a cost of $60 per barrel, in order to replace about 25 per cent of United States oil imports. Against the backdrop of the collapse of oil prices, the programme was cancelled after five years, with production having reached only 10,000 barrels per day and incurred costs having amounted to $5 billion (at 1980 prices) (Gaskins and Stram, 1991). Despite its failure to reach its envisaged goals, the programme did develop coal-gasification technologies that paved the way for highly efficient integrated gasification combined cycle (IGCC) coal power plants which were deployed around the world from the 1990s.

Hydrogen production in the United States

In contrast with the large diffusion investments in ethanol and synthetic fuels, support for hydrogen production and handling (that is, materials science) has been small-scale and limited to R&D. However, hydrogen has found a performance niche in certain industrial processes. Annual production in the United States from 1971 to 2003 increased more than 10-fold and production costs were reduced by a factor of 5, without any subsidies and despite the material challenges associated with handling hydrogen (Ausubel, 2007). A hydrogen pipeline is being operated between Louisiana and Texas; and some are considering the old idea of mixing hydrogen into the national natural gas pipeline system.

Nuclear power in the United States

The fact that, initially, safety was not a key performance criterion for nuclear power has had far-reaching consequences

Experience with nuclear power offers a prime example of an ambitious "big push" experiment which Governments have carried out in order to accelerate development, deployment and diffusion of a new energy technology. As noted earlier, more than half of all cumulative energy-related public RD&D support in IEA countries since 1974 has been for nuclear power technologies. Exuberant expectations by early promoters of nuclear power from the 1950s are reflected in the statement by Lewis Strauss in 1954 that nuclear power would become "too cheap to meter". In the beginning of the 1970s, the International Atomic Energy Agency (IAEA) had expected global installed nuclear power to reach at least 2.5 terawatts (TW) by 2000, as compared with what was in fact the actual total of 351 gigawatts (GW). The first nuclear power plant started operating in the United Kingdom in 1956. In the United States, as many as 65 plants were ordered between 1965 and 1969, and by the end of 1970, the country had 107 units on line, under construction or purchased. Rapid scaling up of unit size to beyond 1 GW brought costs down to less than those of coal power plants in the early 1970s. Thereafter, increasingly large cost and construction time overruns made nuclear power increasingly uncompetitive. Between 1978 and very recently, no new plant was ordered in the United States. Reasons included low oil prices (for much of the 1980s and 1990s) and increasing costs associated with safety regulation. The "Atoms for Peace" programme launched by the United States in 1953 was a typical Government big-push technology undertaking which shortened the formative phase during which, typically, different designs are tested. In the end, the design of the pressurized water reactor used in nuclear submarines became the sole dominant operational commercial reactor design. Yet, it was compactness and little need for refuelling that had been the main performance criteria of reactors in submarines. Safety was not a key performance criterion, which has had far-reaching consequences. When accidents in commercial nuclear power plants made it increasingly clear that safety had to be increased, it was achieved with retrofitting and increased regulation. By the year 1978, an average of 1.3 new regulations were being added *every day* in the United States. The result was the introduction of additional risks related to an increasingly complex technology system and cost overruns due to retrofitting. In short, the well-intended Government push for rapid commercialization of nuclear power without a link to appropriate performance criteria led to lock-in of inferior designs. Alternative designs, such as passive safety systems and high-temperature reactors, came too late.

Wind power in Germany, Denmark, the United States, the Netherlands, China and India

Premature scaling up of inferior technology can be an obstacle to building a sustainable industry

The first wind power plants had been developed in the 1880s, but it was not until the 1970s that the currently dominant design was settled upon and deployed. Denmark, the United States, Germany, the United Kingdom, Sweden and the Netherlands were early movers in wind energy innovation but followed different approaches. In the 1970s and 1980s, Germany and Sweden had focused on public R&D support for a quick scaling up to a range of 2-4 megawatts (MW), but provided only limited support for market formation. Premature scaling up failed to build a sustainable industry (Meyer, 2007) and established utilities had little incentive to deploy high-cost, intermittent wind turbines which were difficult to maintain. Denmark, the Netherlands and the United States focused on R&D and deployment of smaller-scale and simpler wind turbines in niche markets. Denmark established a test station for wind turbines in 1978, issued type approvals from 1979 and introduced investment and production subsidies in the same year (Grübler and others, forthcoming). The result was sustained growth of the industry, the entry of new actors (farmers and municipalities), and very high reliability (98 per cent in 1985) (Heymann, 1998). While the Netherlands had also established a test field in 1981, it focused on competition rather than cooperation among manufacturers, which led to much slower progress and to lower reliability. In the United States, a number of subsidy schemes were introduced that led to a boom in wind power so that, by 1986, California had installed 1.2 GW of wind power which, at the time, constituted 90 per cent of the world total. However, "subsidy harvesting" by the private sector spurred hasty development and inadequate operational testing. By 1985, only 38 per cent of wind-power plants in the United States were operating properly; and the industry collapsed in 1986 when Government subsidies were reduced.

From the 1990s, many increasingly large wind power projects were undertaken in Denmark, Germany and Spain. The cost per kWh of wind power was halved between 1980 and 2000, and reliability, efficiency, level of turbine noise, and grid stability greatly improved. Germany introduced feed-in tariffs, and average wind farm and turbine prices declined by 30 per cent from 1991 to 1996 (a learning rate of 10 per cent), with export prices at about half the average domestic price (Junginger, Faaij and Turkenburg, 2005). Germany's feed-in tariffs effectively cross-subsidized technology transfer and the development of wind power industries in other countries, including China and India. From 1996 onward, prices began to increase in Germany, owing to rapidly expanding demand both domestically and for exports to emerging economies and later owing to higher commodity prices.

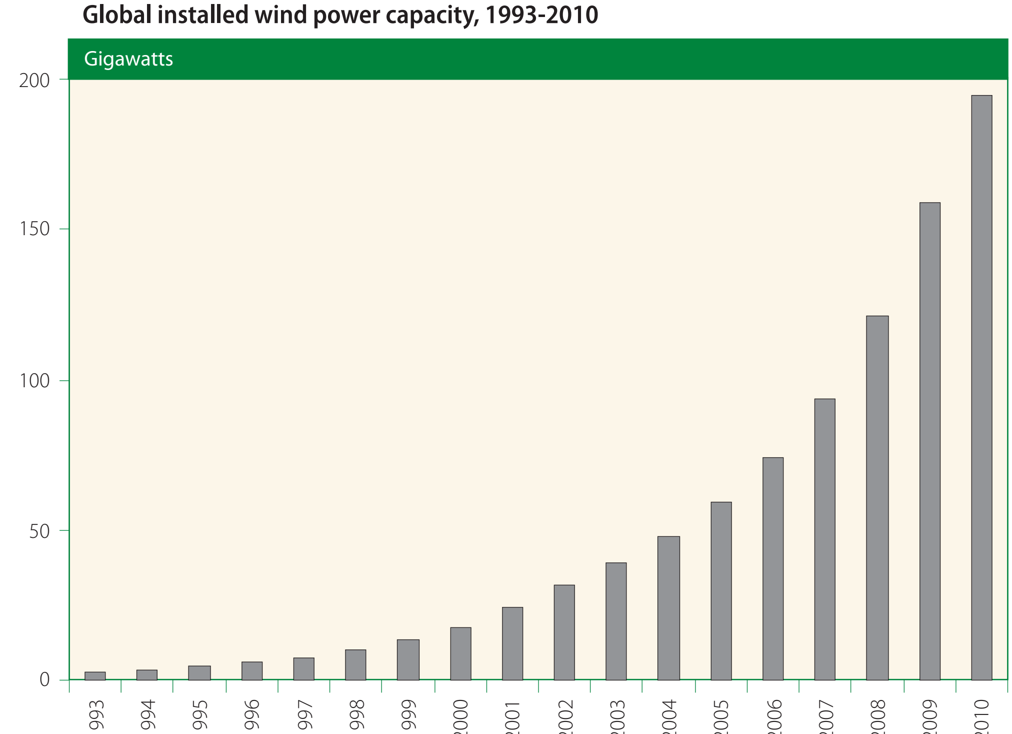
China and India have used industrial policy, including legal provisions, duties, taxes and subsidies, to support domestic wind power research and the wind power industry since the 1990s

China and India have used industrial policy, including legal provisions, duties, taxes and subsidies, to support domestic wind power research and the wind power industry since the 1990s (see chap. V). Further, China mandated domestically produced components and, along with India, instituted domestic technology certification programmes. As in the case of Europe, wind power plants were not necessarily built in the most suitably windy locations: the local policy environment was a much more important factor. For example, in India in 2004, 57 per cent of wind power capacity was installed in Tamil Nadu which only has 7 per cent of the wind resources (Global Wind Energy Council, World Institute of Sustainable Development and Indian Wind Turbine Manufacturing Association, 2011). By the end of 2010, 194 GW of wind power capacity had been installed worldwide (figure II.6), of which 84 GW were in EU, 40 GW in the United States, 42 GW in China and 13 GW in India. In 2010, 35.7 GW of new capacity were installed, which was 6 per cent less capacity than in 2009. More than half of this new capacity was installed in China (16.5 GW) and India (2.1 GW), compared with 9.8 GW in EU and 5.1 GW in the United States (Eurobserver, 2011).

Photovoltaics in Germany, the United States, Japan, China and Kenya

Solar photovoltaics (PV) was invented in the United States but was not deployed there on a large scale. For several decades, through its R&D, and its "Sunshine Programme" from 1994 to 2004, Japan refined the technology and successfully reduced the costs of a 3kW roof system from 6 million to 2 million yen. The Sunshine Programme was remarkable in that it phased out its solar PV subsidies (which peaked at about $250 million in 2001) over

Figure II.6
Global installed wind power capacity, 1993-2010



Source: Eurobserver (2011).

the duration of the Programme. Despite its low insolation levels, Germany is today by far the largest solar PV market in the world, owing to its generous feed-in tariffs. China produces and exports the majority of solar panels, most of which are sold in Germany, which remains the producer of machines needed in the manufacturing plants. Most recently, off-grid solar PV has become increasingly popular in poor areas without access to electricity, in view of the prevailing high electricity prices and low demand levels. The examples of Kenya and Bangladesh are described in chapter V.

Solar water heaters in the United States and China

Research in United States national laboratories and universities had improved solar water heater technology in the 1970s. A key breakthrough was the production of selective coatings which would absorb more sunlight. Driven by United States Federal and State subsidies and expectations of high future energy prices, the solar water heater industry boomed from the late 1970s and a $1 billion industry was created. In the 1980s, there was rampant abuse of generous subsidies (subsidy harvesting) which resulted in poorly installed systems. Within a few years, about half the systems were no longer functioning (Taylor, 2008). In 1984, tax credits for new installations expired and the solar water heater industry in the United States collapsed, with the technology being by and large abandoned for two decades. The perception of poor reliability persists and, with the industry's size currently at about $30 million, has proved difficult to overcome. More successful was a programme in Hawaii that made consumer rebates contingent on an inspection. The technology is currently cost-effective, especially in large installations with high demand for hot water. While the quality of the technology has improved since 1976, unit costs have not been reduced significantly and, instead, have been determined mainly by the price of steel and glass (Taylor and others, 2007). In contrast, solar water heaters have been rapidly adopted in China which now accounts for most of the 100 GW capacity that is installed worldwide today.

More successful than efforts of the United States to improve solar water heater technology was a programme in Hawaii that made consumer rebates contingent on an inspection

Concentrated solar power in the United States, Germany, Spain and North Africa

The United States, Germany and Spain have led long-standing research programmes in solar thermal electricity, which included experimentation with a variety of designs.[8] The first modern concentrating solar power (CSP) plant with 1 megawatt (MW) capacity had been built in Italy in 1968. The parabolic trough design of a 354 MW plant built in California in 1984 became dominant. Different types of working fluids (such as molten salt), which are a key determinant of the efficiency, have been used. Overall deployment remains much lower than that of wind power, owing to higher cost and water-use conflicts in desert areas. In the United States, costs of producing CSP are about 12-18 cents per kWh compared with 2 cents for nuclear power, although costs as low as 5 cents might be achievable in the future with heliostat mirrors and gas turbine technology.

Overall deployment of solar power remains much lower than that of wind power, owing to higher costs and conflicts over water use in desert areas

An industrial consortium, consisting mainly of German companies, has recently been formed with the goal of constructing a country-size CSP facility in North Africa and linking it to the EU power grid with high-voltage alternating current (HVAC)

8 Designs include the parabolic trough, the dish stirling, the concentrating linear Fresnel reflector and the solar power tower.

lines. The initiative is commonly known as DESERTEC. The consortium has plans for a €400 billion CSP facility together with solar PV and wind power over an area of 17,000 square kilometres (km^2) in the Sahara which might deliver as much as 15 per cent of Europe's power by 2050. Besides the costs, the main obstacle to the realization of the DESERTEC goal continues to be geopolitical in nature.

Micro-hydroelectricity and biogas in China

China has the largest hydroelectricity potential in the world. During the "Great Leap Forward" (which started in 1958), there had been plans to build 2.5 GW of micro-size hydroelectricity plants by 1967, but only about 0.5 GW were completed (Carin, 1969). In a new wave of construction from 1970 to 1979, their number increased from 26,000 to 90,000, with mean size doubling to only 70 kW. Much larger hydro plants in the MW and GW ranges have been built since the 1980s. Many technical and maintenance problems (silting, drought, leaks) with hastily built microplants meant low load factors and relatively high costs (Smil, 2010a). In 2006, China completed the world's largest hydropower plant, with a capacity of 18.2 GW. From the early 1970s, China had promoted microscale biodigesters running on animal dung, human faeces, garbage and waste water. A 10 cubic metre (m^3) biodigester was deemed sufficient to provide biogas for a family's cooking and lighting needs. Some 30,000 were completed by 1973 and 400,000 by 1975. China's official target for 1985 was 20 million units, but in reality their numbers fell to less than 4 million by 1984, as millions of the units were abandoned owing to lack of the necessary skills for maintenance (ibid.).

Efficient cook stoves in developing countries

There is a wide range of cooking-stove models tailored to local needs, fuel supply, available technical skills and affordability

The Global Energy Assessment reviewed 51 programmes, conducted since 1980 in 8 Asian, 12 African and 9 Latin American countries, whose aim has been to distribute clean cooking stoves to poor households. Included in the review were costs, efficiency and technologies used. The review highlighted the wide range of cooking-stove models tailored to local needs, fuel supply, available technical skills and affordability. Energy efficiencies ranged from 15 per cent for simple mud stoves running on straw and twigs (several thousands of which were constructed by trained artisans in Viet Nam at a cost of $1.8) to as high as 40 per cent in the case of a programme in China involving 300,000 clay stoves running on coal briquettes and constructed in local workshops since the 1980s. There was no evidence of systematically increased efficiencies or reduced costs over time. Programmes in Latin America tended to be smaller in size, but were mostly subsidized to varying degrees, including 100 per cent in some cases in Guatemala, Bolivia (Plurinational State of) and El Salvador, whereas in Asian and African countries, there was a wide range of subsidy levels, depending on the type of stove. Noteworthy are the large-scale programmes designed to distribute since the 1990s more than 5 million Chulha stoves, running on a range of fuelwood, straw, dung and agricultural waste, with efficiencies between 20 and 28 per cent, and delivered at costs of only $1.80-$4.60, depending on the subsidy levels (which ranged from zero to 78 per cent subsidy). Manufactured metal stoves in India, Zimbabwe, Rwanda, Mali, the Niger, Burkina Faso and Guatemala, were about 10 times more expensive than Chulha stoves, but typically achieved efficiencies that were somewhat higher—close to 30 per cent.

Top Runner Programme on end-use efficiency in Japan

Japan has maintained mandatory energy efficiency standards for appliances and automobiles since 1980, which were not very successful, however, as they were largely based on negotiations with industry. In 1998, Japan initiated the Top Runner Programme to improve energy efficiency of end-use products, as a cornerstone of its climate change policy. The idea is that the most energy-efficient product on the market during the standard-setting process establishes the "Top Runner standard" which all corresponding product manufacturers will aim to achieve in the next stage.[9] Energy efficiency standards are discussed and determined by the Ministry of Economy, Trade and Industry and its advisory committees comprising representatives from academia, industry, consumer groups, local governments and mass media. The scope of the Programme is reviewed every two to three years. It started with 9 products and had been expanded to 21 products by 2009 (Grübler and others, forthcoming). The targeted products account for more than 70 per cent of residential electricity use. To date, all targets set by the programme have been achieved or overachieved. For example, the energy efficiency of room air conditioners improved by 68 per cent, of refrigerators by 55 per cent, of TV receivers by 26 per cent, of computers by 99 per cent, of fluorescent lights by 78 per cent, of vending machines by 37 per cent and of gasoline passenger cars by 23 per cent (Japan, Energy Conservation Center, 2008), representing enormous technical improvements and attaining one of the highest levels of energy efficiency in the world. Yet, it is not clear whether the Programme can be replicated successfully outside Japan. Specific success factors include a limited number of domestic producers with high technological capacity, which were willing to comply with the standards even without sanctions.

Under the Top Runner Programme, the most energy-efficient product on the market during the standard-setting process establishes the standard that all corresponding product manufacturers will aim to achieve in the next stage

Car fuel efficiency standards in the United States

The typical efficiency of United States cars in the early 1970s had been the same as in the 1930s—13 miles per gallon (mpg), which meant 85 per cent of the gasoline was wasted (Smil, 2010a). The Corporate Average Fuel Economy (CAFE) standards, which were introduced in 1975, doubled the average efficiency of United States passenger cars to 27.7 mpg by 1985, but no further improvements were made until CAFE standards were revised in 2007. In fact, the popularity of sport utility vehicles (SUV), vans and pickup trucks depressed United States vehicle fleet efficiency, which reached only 22 mpg by 2006. The 2007 revision of CAFE no longer exempts light trucks classified as SUVs or passenger vans (unless they exceed a 4.5 t gross vehicle weight rating), and the aim is to increase fleet efficiency to 35 mpg by 2020. For comparison, the 1913 Model T Ford, which was the world's first mass-produced automobile, averaged 25 mpg. All new cars in New Zealand currently rate between 34 and 62 mpg. The EU corporate vehicle standard of 130 gCO_2/km, to be achieved by 2012, is equivalent to 47 mpg (or 5 litres (l)/100 km) for a gasoline-fuelled car.

The popularity of sport utility vehicles (SUVs), vans and pickup trucks depressed United States vehicle fleet efficiency

Lessons from market-based measures

Oil price spikes, high gasoline taxes, subsidies and permit trading schemes are "natural" experiments which provide insights into the impact of market measures, such as energy or carbon taxes.

9 The Top Runners set the standard, with consideration given to technological potential. Differentiated standards are set based on various parameters.

Carbon price signals and emissions trading

The volatility of emissions trading schemes holds back investment in low-carbon infrastructure

The social cost of carbon (SCC) corresponds to the externality of a unit of carbon emitted over its lifetime in the atmosphere. Under an optimal climate policy, the emission reduction target should be set so that the cost of reducing emissions (marginal abatement cost) is equal to the SCC. SCC estimates vary. For instance, estimates previously used by the Government of the United Kingdom for policy and project evaluation ranged from $41 to $124 per ton of CO_2, with a central case of $83. Estimates from other models, for example, the Dynamic Integrated model of Climate and the Economy (DICE), are substantially lower. Recently, the market price of allowances in the EU Emissions Trading Scheme (ETS) has fluctuated around $20 per ton of CO_2. With respect to individual behaviour, calculations done by MacKay (2008) suggest that only with very high carbon prices would there be a noticeable impact on activities like driving and flying. For instance, he concluded that at $150 per ton, domestic users of gas would notice the cost of carbon in their heating bills; a price of $250 per ton would increase the effective cost of a barrel of oil by $100; at $370, carbon pollution would cost enough to significantly reduce people's inclination to fly; and at $900, driving habits might be significantly changed. The prevailing allowance prices appear too low to foster "market pull" of low-carbon technologies, and the volatility of emissions trading schemes holds back investment in low-carbon infrastructure.

Emissions trading markets require careful design and a sophisticated regulatory framework which explicitly takes into account strategic gaming behaviour of actors. For example, in the case of emissions trading in Germany, the design of the first National Allocation Plan (NAP I, 2005-2007) led to "windfall" profits for high emitters and further increased an already existing preference for investments in coal compared with natural gas (Pahle, Fan and Schill, 2011). In contrast, alternative allocation rules, such as full auctioning of permits or a single best available technology benchmark, would have substantially increased natural gas investment incentives. A total of 10 coal power plants (11.3 GW) are currently under construction in Germany, and plans for an additional 12 coal power plants exist, which together would account for about 32 per cent of German peak electricity demand in 2008 (Bundesnetzagentur, 2009). In other words, the details of institutional design are at least as important as the overall choice of policy instrument.

Gasoline taxes

In November 2010, gasoline retail prices in different countries ranged from about 2.2 cents to 256 cents per litre, the wide range being due to massive government intervention in the form of gasoline subsidies and taxes (Deutsche Gesellschaft für Internationale Zusammenarbeit, 2011). This wide range is not limited to gasoline retail prices, but is typical of most energy markets. Fifteen countries (mainly oil producers) had "very high subsidies", with retail prices ranging from 1 to 51 cents per litre, which was below the world crude oil price of $81 per barrel at the time. Eight countries (mostly very poor) had retail prices ranging from $0.52 to $0.76 per litre, the latter being the prevailing level in the United States at the time. The majority of developing countries had retail prices ranging from $0.77 to $1.46 per litre, the latter being at the level of the lowest price level in EU (which was that of Romania). A mixed group of countries, including almost all EU members, Japan, high-income oil producers (Norway and the United Kingdom) and a few least developed countries (Senegal and Malawi) had retail prices ranging from $1.46 to $2.54 per litre. High gasoline prices have not halted the growth of vehicle miles in affluent countries, but they have created a preference for smaller and more fuel-efficient vehicles. Nonetheless, absent regulations, income has been the main driver of transport energy demand, regardless of the level of gasoline retail prices.

Many experiences illustrate the limitations of a policy approach based on price incentives

These cases illustrate the limitations of a policy approach based on price incentives. In the context of the debate about a global CO_2 tax, it is useful to note that gasoline taxes were equivalent to carbon taxes of $248 per tCO_2 in China, $451 in Japan, $575 in Germany, $753 in the Netherlands and $832 in Turkey, whereas subsidies for gasoline in the Bolivarian Republic of Venezuela were equivalent to a carbon rebate of $202 per tCO_2.[10] The implied carbon taxes are between 10 and 100 times higher than the prevailing carbon prices under the Clean Development Mechanism or in EU-ETS markets. They are also higher than carbon taxes deemed necessary for the energy sector as a whole with respect to the declared 450 ppmv stabilization, according to most mitigation scenarios (see, for example, Global Energy Assessment, forthcoming; and Intergovernmental Panel on Climate Change, 2001). Yet, only regulatory measures (such as those of the Top Runner Programme in Japan) have had significant impacts on fuel efficiency and emissions of road vehicles.

Feed-in tariffs

Careful design and periodic re-calibration of feed-in tariffs are necessary to ensure that the objectives are achieved at the lowest cost to society

Feed-in tariffs (FITs) guarantee suppliers of renewable electricity a price that covers their costs with a profit, even though the price is higher than that paid for the fossil fuel-based alternative. The FIT consists in either fixed prices based on generation cost, independent of the market (as in Germany), or a fixed premium on top of the market price for electricity (as in Spain). FIT policies have been adopted in some 75 national and subnational (State/provincial) jurisdictions worldwide (REN21, 2010). A study of support policies for electricity from renewable sources in OECD and selected developing countries concludes that jurisdictions with FITs had the highest market growth for renewables and that payments per kWh tend to be lower under FITs than under standard renewable portfolio schemes (International Energy Agency, 2008a). However, as with any subsidy instrument, careful design and periodic re-calibration are necessary to ensure that objectives are achieved at the lowest cost to society, and this requires strong government capacity. Regulatory capture, where entrenched industry interests are able to extract subsidies even after the legislative objective has been attained, is common.

Does every little bit help: a critical assessment of current approaches

The previous section painted a picture of massive Government intervention and private sector responses to the need to promote clean energy technology research, development and deployment in response to the oil crises and the climate change challenge. Yet, energy technology change has slowed considerably at the level of the global fuel mix since the 1970s, and there is no evidence to support the popular notion of an acceleration of energy technology change, either at the fuel or at the sector, plant or unit levels. In order to reconcile these facts, a science-based reality check is needed, in order to assess the implications of current plans and practices.

10 A gasoline tax of $0.01 per litre is equivalent to $4.14 per tCO_2.

Plans need to add up globally

At the most basic level, initiatives need to add up (in arithmetic terms) to the declared ambitions at the national and global levels. Despite impressive growth rates for the diffusion of renewable energy technologies since 2000, it is clear that the current trajectory is nowhere near attaining a realistic path towards complete decarbonization of the global energy system by 2050. Similarly, the renascence of nuclear power has barely made up for losses of older capacities that are increasingly being phased out.

Planetary-scale transformations are required to meet emissions targets

By making simple order-of-magnitude assessments, MacKay (2008) and Smil (2010a) illustrate the infeasibility of prominent existing plans and proposals. MacKay (2008) also traces that contours of low-carbon energy plans for the world, the United States, the United Kingdom and the rest of Europe: the plans add up in terms of global emissions targets, but to achieve these targets, planetary-scale transformations are required. And MacKay shows that existing energy plans do not add up to such a transformation. All actions help but, if small, they help only a little. For example, systematically switching off a phone charger saves about as much energy as is used up in three seconds of driving a car.

At the international level, global environmental problems and especially global warming are often thought of as problems of developed countries, but in fact populous emerging developing economies increasingly dominate growth in global emissions and resource use. Without participation and actions by today's developing countries, no realistic solution is possible to any one of the global environmental problems. For example, the majority of today's energy-related investments are in developing countries. During 2010-2050, the cumulative cost of the energy system (including investment and operating costs) is estimated at about $60 trillion in developed countries and about $80 trillion in developing countries (Global Energy Assessment, forthcoming).

Plans also need to add up at the system level

Plans also need to add up in terms of both the requirements of the energy system and the overall progress measures such as global eco-efficiency, because energy technologies are part of a complex interdependent system and because measures devised to achieve eco-efficiency at the local or even at national levels do not necessarily add up to a globally eco-efficient system.

The net result of a successful national climate policy could be an overall increase in emissions worldwide if production plants are simply transferred abroad

First, plans need to add up in terms of the *global* energy-economy-environment (E3) system. For example, satisfying about 20 per cent of today's demand for gasoline, diesel and kerosene with modern biofuels is possible in technical and economic terms from the perspective of the energy system alone. However, this would likely have enormous impacts on agriculture, food prices, ecosystems, water availability, the nitrogen cycle, energy demand and prices and, most importantly, the livelihoods of the poor in rural and urban areas alike (see also chap. III). Thus, a 20 per cent share might not be enough. With respect to the United Kingdom's climate policy, its implementation has led to decreasing greenhouse gas emissions and the country's early achievement of its commitments under the Kyoto Protocol; but while this achievement is commendable, what needs to be ascertained is whether lower emissions are indeed the result of fundamental changes in technologies or consumption patterns. In fact, when greenhouse gas emissions that are embodied in products that had been imported to the United Kingdom are included, the overall greenhouse gas emissions associated with energy and product demand in the United Kingdom increased by 12 per cent between 1992 and 2004 (Minx and others, 2009). In other words, greenhouse gas pollution was exported abroad. In addition, it is highly likely that such production, most of which was moved to emerging economies, is carried out with lower energy efficiency and higher emission intensities. Thus, the net result of the commendable United Kingdom climate policy was quite possibly an overall increase in greenhouse gas emissions worldwide—the opposite of the objective intended. This example highlights the importance of global coordination and the need for reality checks of measures from a systems and global perspective.

Second, plans also need to add up in terms of the *national* E3 system. One phenomenon to consider in this regard is the "rebound effect" (the Jevons paradox), that is, the increased energy use resulting from increased energy efficiency. While the rebound effect may be small at the local level, it is typically large at the level of the national or of the global economy. Thus, an increase in energy efficiency of a manufacturing plant, while highly desirable from an eco-efficiency perspective at the corporate level, may be partially or wholly offset through reduced energy prices and increased real incomes. Additional measures and regulations are needed to prevent or at least limit the rebound effect.

There is still a relatively large potential for efficiency increases in end-use appliances

At the same time, incentives to increase energy efficiencies are large, especially in end-use. For example, the typical compounded efficiency of the energy chain from crude oil at the well to useful transport services is about 2 per cent only (assuming single occupancy of a passenger car with five seats). While in this case, the efficiency of transforming primary to final energy is as high as 93 per cent (including transport, refining and distribution), the efficiency of transforming final to useful energy efficiency is only about 10 per cent (that is, the result of 20 per cent engine efficiency and 50 per cent efficiency of drivetrain and car). Full occupancy of the car would increase the compounded efficiency from 2 to 10 per cent. In contrast, no conceivable future engine technology could achieve the same overall efficiency increase for a single occupancy vehicle. Engine efficiency would need to be 100 per cent, which is a thermodynamic impossibility. It should also be noted that there is only limited potential for efficiency improvements in power supply technologies, some of which, such as gas combined cycle and integrated gasification combined cycle (IGCC) plants, operate not far from their theoretical limits. Similarly, the so-called cumulative degree of perfection is high for diesel oil and natural gas, compared with other materials, implying only modest room for improvements in this area (Szargut, 1988). In contrast, there is still a relatively large potential for efficiency increases in end-use appliances.

At present, there are no good substitutes for fossil fuels as industrial feedstocks

Third, plans need to add up at the level of the energy systems themselves. For example, at present, there are no good substitutes for fossil fuels as industrial feedstocks. Coke made from coal is needed as a reduction agent for smelting iron from ore. The historical alternative of charcoal cannot be used in modern blast furnaces, and even if it could be used in some form, about 3.5 Gt of dry wood per year would be needed for pig iron smelting alone, which requires plantations that are about two thirds the size of the forests of Brazil. Similarly, there are no plant-based substitutes for hydrocarbon feedstocks (about 100 giga cubic metres (Gm^3) of natural gas per year) used in making plastics and synthesizing ammonia for fertilizer production. As a result, any proposal to phase out fossil fuels requires targeted research into alternative industrial processes.

The installation of a wind farm does not necessarily lead to a reduction in emissions when backup capacity is provided by coal power

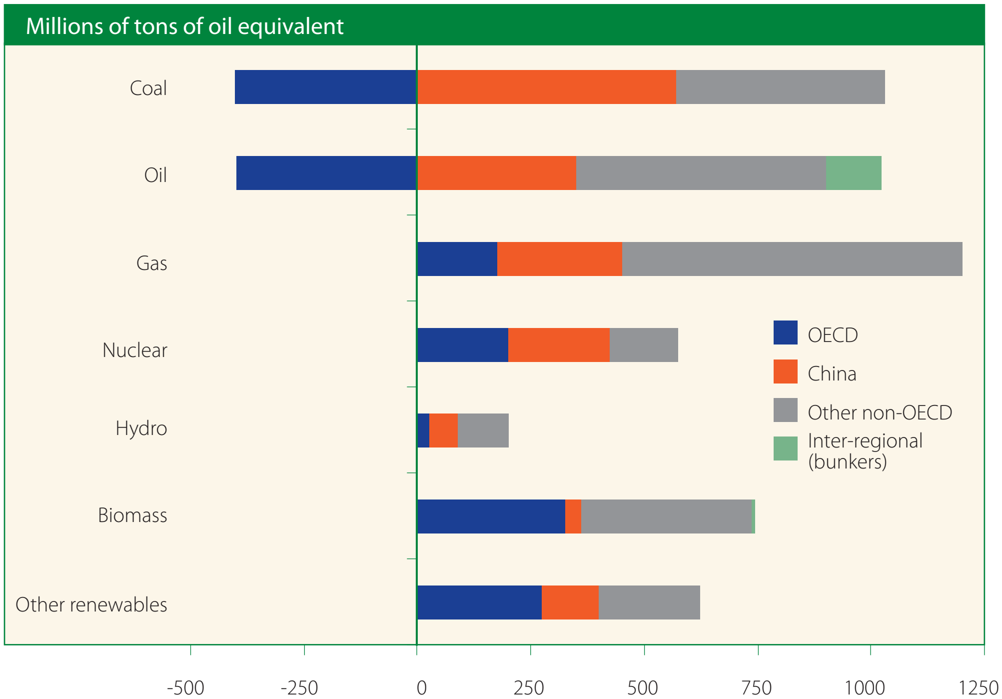
Fourth, plans need to add up at the level of power systems. For example, owing to its intermittency and need for backup capacity, the potential reduction in greenhouse gas emissions that can be achieved by wind power depends almost entirely upon the existing power system to which it is added. In fact, the installation of a wind farm does not necessarily lead to a reduction in emissions, in particular when backup capacity is provided by coal power. The "performance credit" of wind power in Germany was estimated to have been about 10 per cent in 2010 and is expected to fall to 3 per cent in 2030, with increasing installed wind power capacity (assuming a target of 99 per cent power grid reliability) (Deutsche Physikalischen Gesellschaft, 2010). This means that for each GW of newly installed wind power capacity, an additional 0.9 GW backup power capacity (for example, coal, gas or nuclear) is needed to ensure grid reliability, owing to wind's intermittency. Thus, expansion of wind power in Germany (and many other countries) primarily reduces fossil fuel demand, but hardly substitutes fossil-fired power plant capacities in the European grid, which explains the high systemic estimates of CO_2 mitigation costs for wind power of €40-€80 per tCO_2, compared with lower estimates based on assuming a full substitution of fossil-fuelled power capacities (Deutsche Energie-Agentur (DENA), 2005).

Ambitious plans for deployment of intermittent renewables need to be based on plans for the development of smart grids. The Global Energy Assessment (forthcoming) has estimated that the required share of zero carbon energy in 2030 would need to be about 22 per cent, in order for the target of staying below a 2° C increase from pre-industrial levels to be achieved with a probability of at least 50 per cent. Only the most ambitious technology-optimistic scenarios achieve such a high share, as illustrated by a literature review of renewable energy scenarios (Hamrin, Hummel and Canapa, 2007). The most technology-optimistic of the IEA scenarios (IEA ETP tech plus) barely reaches this level; the others include the EU World Energy Technology Outlook-2050 (WETO-H2) scenario with CO_2 constraint, and the Greenpeace "revolution" scenario. Assumptions in these scenarios are heroic indeed, requiring unprecedented technological progress, international cooperation and transfers. The same review also shows that under these and even less ambitious renewable energy scenarios, it is expected that a global share of more than 5 per cent of intermittent modern renewable power will be reached by 2020. This will require some sort of smart grid to deal with load balancing, which in turn means that these scenario plans assume the rebuilding of the existing power grids in most large economies within the next 10 years, an extraordinarily ambitious undertaking (comparable undertakings in previous energy transitions took more than 50 years).

National plans announced across the world do not add up to action sufficient to achieve the global targets for emission reductions

The International Energy Agency (2010b) has presented a "New Policies Scenario", which assumes implementation of recently announced commitments and plans, including those that are being discussed but have not yet been adopted. In this scenario, demand for all types of energy increases in non-OECD countries, while in OECD, demand for coal and oil declines. Globally, most new primary energy demand will be for fossil fuels until 2035, even in this very ambitious and optimistic scenario (figure II.7), which means that, ss a result, fossil fuels would maintain their central role in the primary energy mix, with their share declining from 81 per cent in 2008 to 74 per cent in 2035. Global emissions would continue to rise, but at a decreasing pace, reaching 35 Gt in 2035 (which is 21 per cent higher than the 2008 level). Developing countries would account for essentially all the increase, whereas developed countries' emissions would peak before 2015 and then fall. This would lead to stabilizing GHG (equivalent) concentrations at over 650 ppmv, resulting in a likely temperature rise of more than 3.5° C in the long term. In other words, national plans announced across the world plus what was agreed at the Cancun session of the Conference of the Parties in 2010 do not add up to action sufficient to achieve the global targets for emission reductions.

Figure II.7
Incremental primary energy demand in the IEA New Policies Scenario, 2008-2035



Source: International Energy Agency (2010b).

Feasible timescales for transitions

The comprehensive account given by Smil (2010b) of energy transitions suggests that the scale of the envisaged global transition to non-fossil fuels is about 20 times larger than the scale of the historical transition (fossil fuel use was about 425 EJ in 2010, compared with 20 EJ for traditional biomass in 1890). The physical magnitude of today's energy system based on fossil fuels is enormous, indeed. There are thousands of large coal mines and coal power plants, about 50,000 oilfields, a worldwide network of at least 300,000 km of oil and 500,000 km of natural gas pipelines, and 300,000 km of transmission lines. Globally, the replacement cost of the existing fossil fuel and nuclear power infrastructure is at least $15 trillion-$20 trillion. China alone added more than 300 GW of coal power capacity from 2000 to 2008, an investment of more than $300 billion, which will pay for itself only by 2030-2040 and will run maybe until 2050-2060. In fact, most energy infrastructures have recently been deployed in emerging economies and are completely new, with typical lifetimes of at least 40-60 years. Clearly, it is unlikely that the world will decide overnight to write off $15 trillion-$20 trillion in infrastructure and replace it with a renewable energy system having an even higher price tag. At the same time, it should be noted that the long-term incentive to change the existing energy system should be powerful, too, particularly in view of the fact that oil importers spent about $2 trillion to buy crude oil in 2007.

The growth of modern renewables from 1990 to 2008 was much slower than historical expansions of oil-based energy at 8 per cent per year from 1880 to 1900

Globally, modern renewables (wind, geothermal, solar photovoltaic, solar thermal and modern biofuels) accounted for 0.45 per cent of primary energy in 1990 and 0.75 per cent in 2008, which in relative terms corresponds to an average growth of 2.9 per cent per year. Over the same period, this was faster than the average annual growth of coal (1.6 per cent), crude oil (1.5 per cent) and natural gas (1.2 per cent). In absolute amounts, however, this growth amounted to the addition of 50 Mtoe of modern renewables, compared with much larger additions of coal (760 Mtoe), of oil (1,080 Mtoe) and of natural gas production (990 Mtoe). The growth of modern renewables from 1990 to 2008 was much slower than historical expansions of coal, at 5 per cent per year from 1850 to 1870; oil extraction, at 8 per cent per year from 1880 to 1900; and natural gas production, at 8 per cent per year from 1920 to 1940. Modern renewables (half of which was wind power) accounted for 3 per cent of global electricity production in 2008.

Meanwhile, internal combustion and diesel engines, which were first deployed in the late nineteenth century, still power about 1 billion cars, trucks, trains, ships and heavy machinery, with a combined capacity of about 150 terawatts (TW) (corresponding to 10 times the world's energy demand) (Smil, 2010b). Solutions that do not build on the prevailing prime movers and existing energy infrastructure will require decades to make significant dents in the primary energy mix. Unprecedented and worldwide coordinated measures are needed to transform the global energy system into an almost carbon-free one by 2050.

Small, resource-rich or affluent countries can achieve much faster transitions than large, resource-poor or low-income countries

Completion of some national energy transitions has been achieved more rapidly. For example, following the discovery of the giant Groningen natural gas field in the Netherlands, the natural gas share went from 1 per cent in 1958 to 5 per cent in 1965 and to 50 per cent in 1971. Portugal increased its share of renewables, including hydro, from 17 to 45 per cent in a matter of five years, from 2005 to 2010, and plans to become the first country to inaugurate a national network of charging stations for electric cars in 2011. However, it needs to be emphasized that small, resource-rich or affluent countries can achieve much faster transitions than large, resource-poor, or low-income countries.

One way to speed up the deployment of modern renewables is to rebuild the national grids so as to make them smart as well as to strengthen cross-border power interconnections. Current ambitions would require a rebuilding of the majority of the power grids in the world within the next 10 years, another achievement that would be completely unprecedented, which is not to say that it would be technically impossible, but only that it would come at a significant social and economic cost and would divert resources from other pressing needs, especially those of the world's poor.

Staying within limits

Energy plans must take account of certain types of limits:

- *Biophysical limits*: what is possible within planetary limits and according to the laws of nature?
- *Scientific-technical limits*: what is doable technically?
- *Economic limits*: what is affordable?
- *Socio-political limits*: what is acceptable socially and politically?

Biophysical limits have to be taken into account in making energy plans

When proponents and adversaries of energy technologies make opposing statements about their potential, the differences are often a reflection of the different types of limits that are being considered (MacKay, 2008). For example, a solar power proponent might state that the potential for solar radiation absorbed by land is 790 zettajoules (ZJ), which was about 2,000 times the figure for fossil fuel extraction in 2010. Smil (2010b, p. 110) notes that "direct solar radiation is the only form of renewable energy whose total terrestrial flux far surpasses not only today's demand for fossil fuels but also any level of global energy demand realistically imaginable in the twenty-first century". However, this is what is biophysically available—not what it is technically possible to harness. Leaving aside unsuitable locations constituting about half of the world's land area (those characterized by weak insolation or inaccessibility) about 470 ZJ are available. Yet, it would be technically possible to harness only a small fraction of this, and even less would be economically or politically acceptable. For example, the very ambitious Global Energy Assessment efficiency scenarios assume a techno-economic potential for solar PV, solar thermal and solar water heating of 2.6 ZJ.

MacKay (2008) provides per capita estimates of technical potentials for harnessing renewable energies for Europe, the United Kingdom, the United States and the world. Even leaving aside any economic and socio-political limits, he provides a low-carbon energy plan for the world and estimates the global potential for non-solar renewable energy to be about 83 GJ per capita (table II.3). In other words, without tapping at least some form of solar energy, it is technically impossible to provide for the level of energy use prevailing in Western Europe today. One billion people in Europe and North Africa could

Without tapping at least some form of solar energy, it is technically impossible to provide for the level of energy use prevailing in Western Europe today

Table II.3
Renewable energy plans for the world

	MacKay (2008)			*Riahi and others (forthcoming)*
Renewable source	*Technical potential (EJ)*	*Technical potential per capita (GJ)*	*Comments and assumptions*	*Techno-economic potential for Global Energy Assessment scenarios by 2050*
Wind	189	27.4	Onshore and offshore. Estimate of Greenpeace and the European Wind Energy Association	170
Hydro	28.8	4.11	Estimate by the International Hydropower Association and the International Energy Agency	28
Tide	1.2-2.6	0.18-0.37		..
Wave	3.9	0.57	10 per cent of raw wave power converted at 50 per cent efficiency	..
Geothermal	63.1	9.14	Extrapolation of United States geothermal potential for the world	17
Biofuels	284	41	All of the world's arable or cropland (27 million km^2) used for biofuels! Power density of 0.5 W/m^2, and losses of 33 per cent in processing and farming	117+28
Total non-solar	**571**	**83**	Sum of the above	**360**
Solar photovoltaics (PV)	..	..		1 650
Concentrating solar power (CSP)	..	..		990
Total solar: solar heaters, PV and CSP	**370 EJ**	**>54**	One billion people in Europe and North Africa could be sustained by country-size solar power facilities in deserts near the Mediterranean; and half a billion in North America could be sustained by Arizona-size facilities in the deserts of the United States and Mexico	**2 640**

Source: MacKay (2008); and Riahi and others (forthcoming).
Note: Data converted and adjusted for the world population of 6.9 billion in 2010.

be sustained by country-size solar power facilities in deserts near the Mediterranean; and half a billion in North America could be sustained by Arizona-size facilities in the deserts of the United States and Mexico.

The impacts of such a global energy plan on socio-economic and ecological systems would be enormous. For example, the harnessing of 284 EJ of biofuels would require using all of the world's arable or cropland of about 27 million km^2 for biofuels, which is clearly infeasible. For comparison, the land requirements of today's global fossil fuel infrastructure are less than 30,000 km^2, which is about the size of Belgium (Smil, 2010b). MacKay's order-of-magnitude estimates provide an illustration of the existing technical limits and what, in principle, could technically be achieved with extraordinary political and financial commitments.

Wind requires very large areas of land and power infrastructure to provide power to urban areas

Technical limits of renewables are essentially based on spatial power densities of the technologies, their conversion efficiencies and their deployment potential. Solar power reaches spatial power densities that are two orders of magnitude higher than for wind and three orders of magnitude higher than for photosynthesis. Solar power can in principle reach power densities commensurate with demand densities in houses and some smaller cities. However, industry, high-rise buildings and megacities (in which the majority of the world's population will live) require even higher power densities than solar could offer. These were made available by fossil fuels and nuclear power which exhibit power densities that are higher than the demand of even high-rise buildings (Smil, 2010a). In contrast, wind power or biomass, with power densities less than 0.5 W/m^2, require very large areas of land and power infrastructure to provide power to urban areas. In fact, the energy demand footprint for England and large parts of Central Europe is larger than what it would be possible to provide with non-solar renewables (MacKay, 2008).

Economic limits and affordability receive the most attention in the global debate on the potential for low-carbon energy technologies. While it is correct that, aside from hydro (the potential of which is low but of high quality) and wind (which provides low-quality power), modern renewables continue to be significantly more expensive, economic limits are ultimately a lesser constraint, as they can be overcome with political will and special efforts.

In poorer countries, higher energy prices typically mean higher food prices and, potentially, increased poverty, social conflict and even revolts

Socio-political limits are difficult to overcome. In fact, most energy technology debates completely disregard associated socio-political limits. In pluralistic democracies, the "not-in-my-backyard" (NIMBY) attitude is a powerful factor. There are civil movements against pipelines, coal power plants, wind and solar power plants and, especially, nuclear power installation. Italy has phased out nuclear power and Germany, Sweden and Belgium took phase-out decisions at some point in time. An extreme example involves the licensing of the Konrad radioactive waste depository in Germany which took 25 years and included public consultations with almost 289,387 people who formally raised more than 1,000 issues. Similar NIMBY movements exist against power transmission lines and pipelines. In Germany, there is already a NIMBY movement against CCS long before its commercialization (Roehrl and Toth, 2009). In poorer countries, higher energy prices typically mean higher food prices and potentially lead to increased poverty, social conflict and even revolts.

The NEEDS project of EU quantified the full (direct and indirect) costs for energy technologies used in European countries. In addition, a multi-criteria decision analysis (MCDA) process was organized with decision makers who were given the full information/data on externalities. Decision makers' preference ratings of energy technologies differed greatly from both the direct and the full costs, reflecting different socio-political preferences

(Hirschberg and others, 2009). Such differences are a robust finding across MCDA carried out among utilities and policymakers, both in Europe and in China (Hirschberg and others, 2006; 2009). Such results do not bode well for full-cost pricing solutions to clean energy, because the binding constraint will be socio-political rather than techno-economic.

The proposal by the United Nations Environment Programme (UNEP), but also voiced among the G20, to phase out fossil fuel subsidies offers another example of the importance of socio-political limits. In 2009, most of global fossil fuel consumption subsidies amounting to $312 billion were in developing countries. Of this amount, oil products received $126 billion, natural gas $85 billion, fossil-fired electricity $95 billion and coal $6 billion. Fossil fuel consumption subsidies in countries with low levels of access to modern energy[11] amounted to $71 billion, and subsidies in these countries for residential use of kerosene, electricity and liquefied petroleum gas (LPG) (sometimes labelled "fuels for the poor") were less than $50 billion (International Energy Agency, 2010b). Thus, the problem of energy access is one mainly of distribution, not of absolute amounts of available resources. IEA estimates that universal access to modern energy services could be achieved by redistributing just 12 per cent of fossil fuel consumption subsidies in developing countries so as to deal with this problem in the poorest developing countries.

The problem of energy access is one mainly of distribution, not of absolute amounts of available resources

Limits to improving energy efficiency

As discussed above, energy-efficiency improvements when combined with limits on energy consumption have great potential to help achieve global targets. However, it is clear that there are a number of barriers to deployment and adoption of more efficient energy converters, as well as techno-economic limits to be considered. Solutions to overcoming the known barriers exist, but they require long-term commitment and a stable systemic approach by decision makers.

Technical limits to energy efficiency improvements must be taken into account. In 2005, the overall efficiency of global energy conversion (from primary energy to services) was about 11 per cent (Cullen and Allwood, 2010a). In other words, global primary energy demand could be reduced to only one ninth, while the same energy services were provided, if all energy conversion devices were operated at their *theoretical* maximum efficiency. In more practical terms, but still assuming an almost perfect world, global primary energy demand could be reduced by 73 per cent (or to less than one fourth), while the current level of energy services were provided, mainly through a shift to passive systems (Cullen, Allwood and Borgstein, 2011). This is in line with the popularized overall "factor 4" and "factor 5" improvements (von Weizsäcker, Lovins and Lovins, 1998).

If all energy conversion devices operated at their theoretical maximum efficiency, global energy demand could be reduced to one ninth of current levels

In 2005, primary-to-final exergy conversion efficiency was as high as 67 per cent (fuel losses, generation and distribution losses) but final-to-useful exergy conversion efficiency was only about 25 per cent (from conversion loss). Thus, 509 EJ primary exergy provided only about 86 EJ of useful exergy (in the form of motion, heat, cool/light/sound and other non-energy forms), while 128 EJ were lost in combustion, 173 EJ in heat transfer and 123 EJ through electric resistance, friction, fission and other fuel-related phenomena. In addition, a system loss is incurred in converting useful energy into final services ("service efficiency").[12]

11 Defined as countries with electrification rates of less than 90 per cent or with access to clean cooking facilities of less than 75 per cent.

12 Global energy-related services provided included passenger transport, freight transport, structure, thermal comfort, sustenance, hygiene, communication and illumination (Cullen and Allwood, 2010b).

It is important to consider the compounding of energy efficiencies across the chain. For example, if the conversion loss of each device in the chain had been reduced by only 1 per cent (and commensurate limits applied so as to avoid invoking the Jevons paradox), about 33 EJ, or 7 per cent of world primary energy of 475 EJ, could have been saved—an amount almost equal to the energy demand of China at the time. In this example, upstream (fuel transformation and electricity generation) efficiency gains would save only 5 EJ, whereas downstream (end-use conversion devices) efficiency gains would be much larger, at savings of 28 EJ (Cullen and Allwood, 2010b).

It is through efficiency improvements in electric heaters, diesel engines, electric motors, biomass burners, gas burners and factory equipment that the highest potential savings would be achieved

Cullen and Allwood (2010b) estimated and ranked the cumulative global conversion losses of end-use devices along their energy chain, relative to their theoretical ideal (table II.4). The table shows the highest potential savings that would be achieved through efficiency improvements of electric heaters, diesel engines, electric motors, biomass burners, gas burners and Otto engines. The smallest absolute gains were possible with light devices, electronic devices and aircraft engines. In other words, current policies focusing on energy-efficiency improvements in light bulbs, standby losses and aircraft engines are expected to add up to little on the global level.

Table II.4
End-use devices ranked by their cumulative global conversion losses along their individual flow paths

End-use device	*Efficiency (percentage)*	*Loss (EJ)*
Electric heater	7	54
Diesel engine	20	47
Electric motor	17	46
Biomass burner	6	46
Gas burner	12	41
Otto engine	12	36
Cooler	2	33
Coal burner	17	26
Oil burner	14	24
Heat exchanger	2	20
Light device	4	17
Electronic	2	16
Aircraft engine	25	8
Other engine	18	8

Source: Cullen and Allwood (2010b).

Policy options and recommendations

Energy technology innovation matters. It concerns everyone and is often highly politicized. Energy technology policy needs to be comprehensive and supported by industrial policy, especially in the context of support at the market formation phase of technology life cycles (chap. V). Most importantly, global and national energy policy is also development policy and thus must demonstrate special consideration of the poor. Governments need to devise institutional designs that ensure a science-based reality check of energy technology policies. A wide range of policy instruments are available, including economic instruments, regulatory measures and cooperation (table II.5). Optimal policy packages

Table II.5
Examples of public policy measures for inducing the sustainable energy transformation

<table>
<tr><th>Type</th><th>Category</th><th>Examples</th></tr>
<tr><td rowspan="4">Economic Instruments</td><td>Subsidies</td><td>Gasoline subsidies
Feed-in tariffs
Fiscal incentives
Direct subsidies to R&D
Loan softening/guarantees
Subsidies for public transport for the poor</td></tr>
<tr><td>Taxes</td><td>Gasoline taxes
R&D tax credits
Carbon taxes</td></tr>
<tr><td>Permit trading</td><td>Carbon trading market
Renewable energy credit trading</td></tr>
<tr><td>Public procurement/ investments</td><td>Green procurement
Public investment in R&D infrastructure
Government funding of demonstration projects
Government-sponsored R&D, national laboratories
National/State-funded or -run venture capitalism
Public investment in education and training
Government investments in science and technology parks</td></tr>
<tr><td rowspan="2">Command-and-control measures</td><td>Standards and regulations</td><td>Standards for biofuel blending
Energy-efficiency standards
Renewable energy obligations
Cooking stove standards</td></tr>
<tr><td>Goals and targets</td><td>Sectoral energy intensity targets
Greenhouse gas mitigation targets
Energy access targets</td></tr>
<tr><td rowspan="2">Cooperation</td><td>Domestic</td><td>Promotion of collaborative RD&D
Public-private partnerships and knowledge exchange</td></tr>
<tr><td>International</td><td>Official development assistance (ODA) for energy access and clean technologies
Trade preferences for specific technology clusters
Bilateral and plurilateral agreements on technology cooperation</td></tr>
</table>

Source: World Business Council for Sustainable Development (2011).

depend strongly on a country's institutions, development stage, resource endowments and socio-political preferences, and will change over time. In-depth analysis needs to be included in the process of designing policy packages, while simplified prescriptions can be counter-productive. However, insights from past experience suggest broad guiding principles and performance targets which should guide the analysis (Grübler and others, forthcoming; Wilson and Grübler, 2010).

The need for comprehensive, strategic and system approaches

Comprehensive, strategic and systems approaches are needed (see chap. V for further details). The choice of individual technology-related policy instruments needs to be tailored to technology and national and local circumstances. Ignoring the systemic characteristics of technological change often leads to a partial view and fragmented or even contradictory policies. Simplistic approaches need to be avoided, as they are commonly based on

Ignoring the systemic characteristics of technological change often leads to a partial view and fragmented or even contradictory policies myths rather than factual evidence. The co-benefits of comprehensive approaches can be substantial. For example, the costs of halving premature deaths due to air pollution by 2030 and of ensuring energy security could be reduced to one fourth, if these goals were pursued jointly with ambitious greenhouse gas reduction measures. Bringing universal access to electricity and modern cooking fuels by 2030 would not be in conflict with the other objectives (Riahi and others, forthcoming).

Learn from but be aware of the inevitable discontinuities of the historical past

Policy-induced scaling up and deployment of new technologies without lengthy formative periods of experimentation and testing could lead to additional risks and might lock in inferior technologies (Wilson, forthcoming). Historically, performance and quality advantages of new energy technologies compared with the lower energy quality (intermittency and low power density) of modern renewable energy technologies, led to their early adoption among price-insensitive consumers. Fossil fuel resource constraints together with externality pricing might make renewables more cost-competitive, but competing land use will be a constraint on the large-scale deployment of renewables. Also, overcoming vested interests is essential, in view of the fact that, historically, it is political efforts and public infrastructure investment that have set innovator countries apart from laggards (Moe, 2010).

Manage uncertainties with portfolio diversification, scenario analysis, and a balanced mix of technology-neutral and technology-banded approaches

Picking technological winners ex ante should be avoided, while developing broad technology portfolios should be promoted. Doing this will provide a hedge against the risks of inherently uncertain outcomes of technological innovation. Failures vastly outnumber successes in both the private and public sectors. Sufficient time and resources need to be committed for experimentation before scaling up, so as to prevent any premature locking in of suboptimal technologies and clusters (van den Bergh and others, 2007).

Technology portfolios should represent the whole energy system and consider all innovation stages

Technology portfolios should represent the whole energy system and consider all innovation stages, so as to keep options open, but should avoid large-scale transfer of technology risks to the public sector. It should also be noted that less capital-intensive, smaller-scale (for example, granular) technologies tend to be associated with lower overall risk. Scenario analysis can be used for risk hedging through identification of "robust" technology portfolios. In this context, a careful balancing of technology-neutral policies (for example, carbon taxes) and technology-banded ones (for example, feed-in tariffs), as well as short- and long-term policy targets, should be considered (Sandén and Azar, 2005).

Pursue policies that promote high-performance innovations in niche markets

Policies designed to create market niches based on superior-quality technologies should be prioritized in order to shield them from full commercial competition during the initial development stages when experience is gained (Schot and Geels, 2008). At present, there are only a few evident niches in which cost-insensitive end-users might be persuaded to pay for environmental public goods.[13] Historical evidence supports the market niche approach and illustrates the practical problems associated with efforts to "buy down" the learning curve in order to reduce unit costs. New technologies may not need subsidies if they exhibit high performance despite much higher costs.

Pursue innovation policy that is stable, credible, aligned and well timed

Policies should be avoided that compress the formative phase unduly and support premature scaling up

Stable and consistent expectations about the direction and shape of the innovation system, in contrast with existing practices which are mostly characterized by stop-go policies, are necessary if innovation actors are to commit resources (Bosetti and Victor, 2011). Innovation policies need to be aligned, which requires coherent support throughout the technology life cycle, but misalignment appears to be the norm in most countries.[14] Dynamic technology standards can be effective, as evidenced by the Japanese Top Runner Programme for energy-efficient appliances. It is important to choose realistic goals for technology programmes and to manage the expectations of innovation system actors, since programmes have often been discredited in the past simply because they did not achieve their irrationally exuberant goals. Most importantly, policies should be avoided that compress the formative phase unduly and support premature scaling up, as does the current approach taken in promoting CCS, for instance.

Innovations in end-use technologies are important

Public innovation expenditures for highly energy efficient end-use technologies need to be increased. Support for such technologies in the past has proved both cost-effective and successful, thereby generating high social returns on investment (Fri, 2003). Much greater emphasis needs to be put globally on improving end-use energy efficiency, complemented by behavioural change and limits imposed on energy, land, water and materials use.

A global "Top Runner Programme"

A global programme that follows the rationale of Japan's Top Runner Programme should be considered. Such a programme would promote cooperation among countries, communities and individuals so as to achieve lower primary energy use and lower greenhouse gas emissions. Those with the best performance in groups with similar characteristics would successively set the standard for the next phase which laggards will aim to achieve. For example, Japan might be the top runner that sets the standards and targets to be achieved by other technologically advanced economies in terms of end-use energy efficiency. Other examples might include business people responsible for highly energy-intensive patterns of consumption of transport services, or high-income house-owners.

A reasonable primary energy use limit could provide powerful incentives to increase energy efficiency

Furthermore, the programme might also strive to achieve individual primary energy use and greenhouse gas emissions targets. Given the already indicated technological limits to fast-tracking the sustainable energy transformation, per capita caps on energy use and emissions may be needed to ease the challenge. The above analysis suggested that

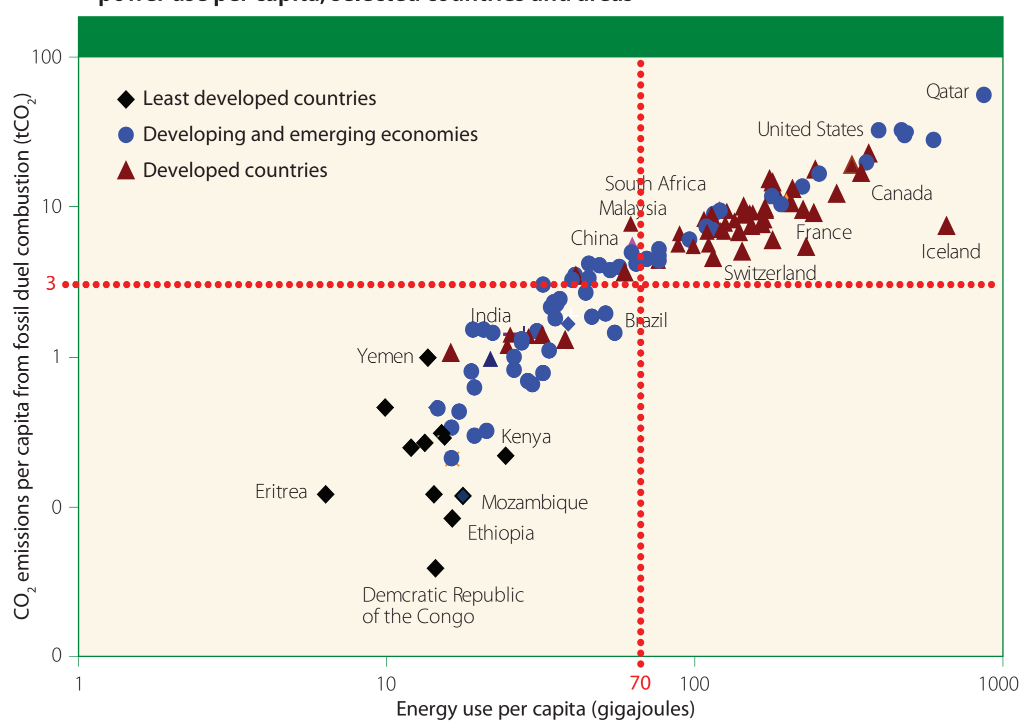
13 Some examples are: no fuel inputs (solar PV in remote off-grid applications), quiet operation (nuclear power in submarines) and storage capacity (fuel cells for grid backup).

14 For example, support for low-carbon technologies is undermined by fossil fuel subsidies and efficiency improvements in transport are swamped by higher demand.

a limit of 70 GJ per capita would seem a reasonable long-term target to be achieved by 2050. This limit would be similar to the figure for the present per capita primary energy use in China and that for the world average (figure II.8). It should be noted, however, that the suggestion is for a limit on primary energy (not final energy), which is most relevant for the environmental impact. In fact, a reasonable primary energy use limit could provide powerful incentives to increase energy efficiency and could ensure the continued provision of more and better energy end-use services despite lower primary energy use.

In environmentally conscious Western European societies, such as that of Denmark, primary energy use is at about 150 GJ per capita, which could be brought down to the 70 GJ target with increased energy efficiency combined with measures to minimize the rebound effect. This would be much more of a challenge for the United States, which currently uses 340 GJ per capita. Such a limit would still allow ample space for energy demand growth in poor countries, such as India, with a per capita use of only 15 GJ. The target of 70 GJ per capita primary energy use would ideally be applied as averages not to countries, but to individuals, in line with the principle of individual fairness. Energy use within countries is highly uneven, with the world's richest 500 million people (7 per cent of the world population)—who live in both developed and developing countries—using more than half of all primary energy (Pacala, 2007). Burden-sharing among countries based on the principle of individual fairness would differ significantly from sharing based on countries' averages, except for the poorest countries which would have almost no commitment either way.

Figure II.8
National greenhouse gas emissions per capita versus power use per capita, selected countries and areas



Source: World Bank, World Development Indicators, 2011. Available from http://data.worldbank.org/data-catalog/world-development-indicators.

Higher energy efficiency and lower primary energy use would take much of the pressure imposed by the imperative of rapid decarbonization off highly energy-intensive economies. Indeed, this chapter has provided ample evidence for why it might prove impossible to achieve the desired pace of global energy transition towards low-carbon and renewable energy without limits on primary energy use. A recent study on how to achieve a 100 per cent renewable energy system in Denmark by 2050 concluded that such an envisioned outcome was realistically achievable only if primary energy use was halved to 70 GJ per capita (Lund and Mathiesen, 2009).

Higher energy efficiency and lower primary energy use would take much of the pressure imposed by the imperative of rapid decarbonization off highly energy-intensive economies

Closely associated with the target of energy use per capita would be a *cap on individual CO_2 emissions of 3 tCO_2* to be achieved by 2050.[15] Such a limit would again be ideally based on individual fairness, rather than fairness across nations. From 2007 to 2030, such limits would then touch only people with annual earnings of more than $40,000 per capita (in PPP terms). For comparison, in 2007, the figure for average energy-related CO_2 emissions per capita[16] of the 60 poorest countries and areas was less than 1 tCO_2. It was 1.4 tCO_2 in Viet Nam and India; 1.9 tCO_2 in Brazil and Indonesia; 2.3 tCO_2 in Egypt; 3 tCO_2 in Mauritius and French Polynesia; 5 tCO_2 in Switzerland, Sweden and China; 6 tCO_2 in France and Venezuela (Bolivarian Republic of); 7.7 tCO_2 in Iceland and Italy; 10 tCO_2 in Germany, Japan, the Russian Federation and the Republic of Korea; 19 tCO_2 in the United States and Australia; 20 tCO_2 in Brunei Darussalam; and as much as 55 tCO_2 in Qatar (United States Department of Energy, Carbon Dioxide Information Analysis Center, 2011).

Among major global scenarios, the Global Energy Assessment mix scenario appears to be roughly in line with the focus and targets proposed here. The scenario foresees cumulative global energy-related investments of $65 trillion between 2010 and 2050, or about $1.6 trillion per year. About $23 trillion of this amount would be needed for improving efficiencies, $12 trillion for smart grids (transmission and distribution), $8 trillion for renewable electricity and a combined amount of $4 trillion for fossil-fired and nuclear power plants. An amount of $13 trillion would be needed for fossil fuel extraction and $2 trillion for biomass-related technology deployment (Riahi and others, forthcoming).

Global energy-related investments of $65 trillion between 2010 and 2050, or about $1.6 trillion per year, are required

"Reality checks" through independent centres for energy systems analysis

Conceptually, policymakers could mandate technology-neutral performance targets and avoid favouring any specific technologies. They would still become involved in all phases of the innovation cycle, in order to ensure coherence and continuity, but would focus resources on research, development and possibly demonstration. In practice, most countries are already engaging in picking winners, directly or indirectly. In late industrializing countries which can draw on existing technologies, current information about these technologies will reduce the uncertainties associated with investing in specific sectors. This makes it particularly important that technologies-related information be accessible at reasonable cost to developing countries and not unduly restrained by private intellectual

In practice, most countries are already engaging in picking winners, directly or indirectly

15 Pacala (2007) suggests that a "fair" personal CO_2 emissions limit be brought down to 3.6 tCO_2 over the next 50 years, in order to reach stabilization of concentrations at 450 ppmv. However, considering the uncertainty surrounding climate change projections and applying the precautionary principle, setting the target at 3 tCO_2 per capita by 2050 would ensure a sufficiently high probability that the stabilization target could be achieved (Jonas and others, 2010).

16 All emission estimates are production-based. Only the United Kingdom has useful numbers of greenhouse gas emissions based on consumption.

property or monopolistic practices. Even in advanced countries, the practice of picking winning technology is perceived to be unavoidable. The important questions would be who should do the picking—and how. In general, policymakers should focus, preferably, on setting broad political goals, rather than on detailed technology-specific issues. Strategic long-term planning is essential in order to coordinate actions by many different actors in different parts of the complex, interdependent energy system. Markets can help coordinate to some extent, but no market has ever been devised that could efficiently coordinate the evolution of the global energy system towards achievement of global policy objectives.

In the majority of developing countries, Governments continue directly or indirectly to "run" the energy system (apart from some regulated independent power production). Energy and economic planning units typically provide in-depth assessments of government plans and targets. While, in theory, energy plans would be based on their independent assessments, in practice, energy planning units are not always independent and assessments are either tweaked to support political decisions or sidelined.

Energy assessments undertaken by academics are not necessarily independent

In countries with liberalized energy markets, Governments have also picked winners directly (for example, through feed-in tariffs or renewable energy standards) or indirectly (for example, through institutional design). These countries typically abolished planning units a long time ago, with analysis being carried out by academic institutions and, more recently, by regulators. However, in-depth energy assessments undertaken by academics are not necessarily independent, since they are typically funded through extrabudgetary resources provided by Governments, professional associations or lobbyists. Further, regulators are (typically) responsible only for subcomponents of the energy system (for example, electricity markets) and have strategic interests of their own.

Hence, Governments, regardless of the level of market liberalization and development stage, might consider the creation of *energy system analysis centres with full independence from politics* which ensure reality checks and alignment of policies and initiatives. These centres would also promote global coherence and compatibility with green growth and sustainable development aspirations, through participation in a global network. A global hierarchy of eco-efficiency targets might be a simple means of systematizing coordination.

One size does not fit all

By their very nature, energy policy interventions will induce structural economic change. Energy policies also tend to have strong distributive effects, benefiting some industries and household groups more than others. The degree and nature of the required structural change related to a sustainable energy transformation will also vary from country to country. The distributive impacts will also differ accordingly.

Poorer and more vulnerable countries require enhanced support from the international community

The sustainable energy transition offers significant economic opportunities for both developed and emerging developing countries, but poses additional development challenges for the poorer and more vulnerable countries, which would require enhanced support from the international community.

Table II.6 provides a highly stylized presentation of the potential impacts for groups of countries, classified for present purposes by income level and status as net fuel exporters or importers. Clearly, the global and national distributive effects will depend on a range of factors such as the degree of dependence on fossil fuel imports and exports, the expected economic growth impacts of local technology capacity development,

Table II.6
Stylized potential impacts of sustainable energy transitions, by groups of countries

Driver	*Country group*					
	Low-income		*Middle-income*		*High-income*	
	Oil/commodities exporters	*Oil/commodities importers*	*Oil/commodities exporters*	*Oil/commodities importers*	*Oil/commodities exporters*	*Oil/commodities importers*
Energy import and export bills (oil price and quantities)	No significant change expected, since mainly medium-cost producers	Lower import bills	No significant change expected, since mainly medium-cost producers	Lower import bills	Export revenues reduced for high-cost producers (for example, in the North Sea area, Canada), and no significant change for low-cost producers (Middle East)	Lower import bills
Economic growth impacts of development of local technology capacities	Possibility of using recent oil/ commodity gains to diversify into green technologies. Huge challenge of competing with emerging economies	Serious challenge in any case	Potential for leadership in "green" technologies development and manufacturing, due to rapidly growing markets, relatively low costs		Challenge associated with opportunity to diversify into green technology niches linked to existing oil infrastructure; for example, in places with high isolation; and develop and deploy solar reactors for the purpose of delivering synthetic gasoline	Continued challenges of deindustrialization and offshoring independent of transition. Can leverage research to maintain technological leadership
Manufacturing, industrialization and deindustria-lization (for example, offshoring)						
Policy-related markets (for example, carbon trading)	Depends on details of market energy					
Poverty, employment and social impacts	Intercountry distribution depends on many factors (for example, climate vulnerability). Intracountry distribution depends on national socio-economic policies and measures					
Unequal distribution of pollution impacts						

Source: UN/DESA.

and opportunities for countries to attract manufacturing of new technologies in efforts to industrialize. Estimating the welfare and distributive effects of those challenges and opportunities is not the purpose of this *Survey*. Yet, such effects will need to be fully considered when designing global and national policies.

The fact that major emerging economies have large markets for energy technologies provides an opportunity to develop local technology capacities and upgrade industrial capabilities

The fact that the major emerging economies have large markets for energy technologies provides an opportunity to develop local technology capacities and upgrade industrial capabilities, as is the case for China. Oil-rich countries with high insolation would also have a number of opportunities to diversify their industrial base and leverage the existing oil infrastructure (for example, through manufacturing and deployment of solar reactors in desert areas near existing oil facilities, with the reactors transforming CO_2 and water into gasoline).

At present, those opportunities would be considerably greater in the case of innovation of new technologies, since the market and intellectual property position in mature technologies is dominated by firms in the developed world.

The sustainable energy transition poses challenges to the poorest countries which face greater obstacles (including small market size) in developing local technology capacities. Industrialized economies would continue to face the challenges of deindustrialization and offshoring, trends which are independent of the sustainable energy transitions, and their main opportunities will be in leveraging their highly developed research capacities so as to maintain technological leadership in technology-intensive market segments.