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Round Table on Sustainable Development

DO WE HAVE THE RIGHT R&D PRIORITIES AND PROGRAMMES TO SUPPORT THE ENERGY TECHNOLOGIES OF THE FUTURE?

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I THE ARGUMENT SUMMARISED

The attached paper brings together three sets of information:

- the technical potential of new energy sources;
- their likely distance from being able to penetrate the market commercially; and
- the level of resources, public and private, presently committed to researching, developing and deploying these technologies.

None of this information is new – it has not been within the Round Table's resources to commission new data. But bringing the information together in this way may be new. Because this paper has been written to animate a cross-disciplinary discussion, we thought it might be useful to highlight at the outset the key issues that emerge from the data, and some of the popularly-held beliefs with which they conflict. Our aim has been to bring together in one place information which allows the key players to discuss these questions:

1. Are there technical possibilities within reach that would enable us to meet expected demand for energy in more secure and less polluting ways? (parts III and IV)

2. Are global investments in researching, developing and deploying these technologies focused where they are likely to leverage the most significant gains, and is the critical mass of investment sufficient given the timescales in which we may wish to effect changes to the energy supply? (part V)

These questions immediately beg a prior question: why should this even be a matter of concern? Two frequently raised concerns form the basis for this paper and the meeting of the Round Table. The first is security of supply. This arises principally in respect of the concentration of remaining oil supplies in politically unstable regions of the world. How can the world's leading economies insulate themselves from the risk of disrupted energy supplies?

The second is sustainability given the need to stabilise atmospheric concentrations of greenhouse gases at levels that minimise the risks of significant climatic disruption. How can the global economy satisfy a strongly rising demand for energy services without a huge increase in total greenhouse gas emissions?

In respect of the first question, the paper concludes that security of supply is not a particularly significant problem in the medium to long term. While oil and (to a lesser extent) gas supplies are certainly concentrated in geo-politically sensitive regions, future demand for liquid and gaseous fossil fuels can be supplied from coal. Indeed, all fossil fuels are substitutable for one another and the technologies needed for those substitutions are available and (at current oil prices) economic.

The second question, satisfying future demand without a massive increase in emissions, is less easily disposed of. Despite efforts that now span more than 15 years, countries have found it extremely difficult to construct a regime that will limit emissions. On a business as usual basis that takes account of current limitations commitments and the historical rate of technological change, emissions are still set to rise by more than 80% by 2030 over 1990 levels. While efforts to avoid emissions will no doubt continue, the implicit (and increasingly explicit) conclusion is that governments are relying on technology to provide solutions, not treaties.

For many observers this raises a classic catch-22 situation. Without new technologies that can limit emissions affordably, negotiators will not have the confidence to conclude limitations agreements. But without limitations on emissions, new technologies will not come forward – or at least, will not come forward anywhere near fast enough.

In assessing the prospects for new technologies, it is important to have a clear understanding of the strong competitive edge traditional fossil fuels have in the marketplace. Their abundance and affordability – and the sheer scale of the investments made in them over several generations – make an easy move away from them hard to envisage. With this in mind it is worth noting some popularly held misapprehensions:

The world depends on cheap and abundant Middle Eastern oil to sustain the transportation sector.

It is often assumed that there is no way the world can move away from Middle Eastern oil without raising the price of transportation fuels substantially. In reality, the price of alternatives to oil as the base feedstock for transportation fuel – such as tar sands and coal – are already competitive when the oil price is in the range of $25 - $40 a barrel. This would indicate a ceiling on the price of oil from OPEC countries in the middle to longer term.

From this perspective, security of supply concerns start to diminish. The distribution of unconventional oil and coal is so widespread that the production of liquid fuel based on these resources would not be regionally concentrated.

Rising oil prices will hasten the advent of a raft of new transport fuels with low or even near-zero carbon emissions

This follows on from the preceding point. While rising oil prices will certainly provide a spur for greater vehicle efficiency, the ability to convert resources such as coal and gas into liquid fuels competitively at well below today's peak oil prices means that the next generation of motor vehicles will not have radically different emissions.

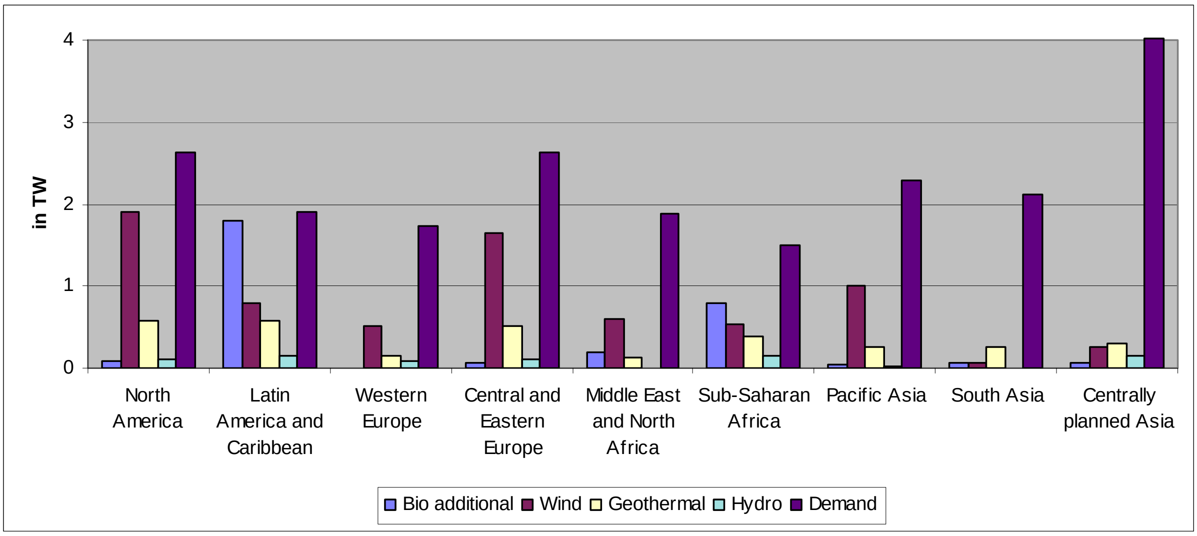
A much talked about option in this regard is bio-fuel. While bio-fuel will be a useful and cleaner addition to liquid fuel in those countries where it can be produced cheaply (such as Brazil), it is very unlikely to be able to replace fossil carbon fuel on account of the requirements for land. Even significant technological advances such as the conversion of cellulose to ethanol will not provide a complete solution given the significant uncertainties that surround just how much photosynthetic activity at the planetary level can be practically diverted to this purpose[1].

Electricity generated from renewable energy can meet future demand.

Renewable energy is in almost all cases more expensive to produce than energy from fossil sources. And it would only be possible – at least in theory – to meet future demand from renewable sources if there was widespread recourse to solar energy. This is the one renewable source that is superabundant although there are non-trivial issues relating to both transmission and storage. Wind, bio-energy and unconventional geothermal energy suffer from greater limitations.

The following table indicates the regional resource availability of renewables if solar potential is excluded (see also part III.6).

Figure A Resource Availability and Projected Demand for Renewables (Excluding Solar) in TW



Rising energy prices and technological developments will ensure that the next wave of electricity generation technologies will be much less carbon-intensive.

From an economic point of view, fossil fuel electricity plants, especially combined cycle gas turbine plants, will most likely remain the technology of choice because of their low overall cost. However, even if the cleanest and most efficient clean-coal power or gas production technologies were to become commercially available and replace existing power plants in the years ahead, the reduction of CO_2 emissions from electricity power generation would probably be not more than 15% in 2020. While this would be a very significant achievement in itself, it must be set against a baseline scenario in which absolute emission levels are still rising and will continue to do so, only at a slower pace.

It is hard to avoid the conclusion that in the absence of any decisive policy intervention the global economy will remain heavily dependent on fossil fuels. Their share could in fact increase if existing nuclear power plants are not replaced with new ones. The next generation of energy technologies will almost certainly be incrementally more efficient but the gains from that efficiency are almost certainly going to be swamped by the sheer increase in generation. It is sobering to reflect on the implications of projected demand. Primary global energy demand is presently around 15TW. That is forecast to double to around 30TW by 2050 (based on moderate assumptions for population growth and economic development). Currently, only about 3TW of the 15TW global demand is met from carbon-free supplies.

Stabilising CO_2 concentrations at twice the world's pre-industrial level in 2050 would imply supplying carbon free energy in 2050 on a scale equivalent to the entire current supply of energy from fossil, nuclear and renewable primary resources. (Part II) Given the cost and variability of many renewable energy sources, a likely on-going reliance on fossil fuels places particular urgency on proving the practicality of large scale carbon capture and storage (CCS). While the present cost of CCS is in the region of 2-3 $cents/kWh and projected to decline to 1-2 $cents/kWh, this is likely to remain significantly cheaper than electricity from renewables that will have higher additional costs in most locations.

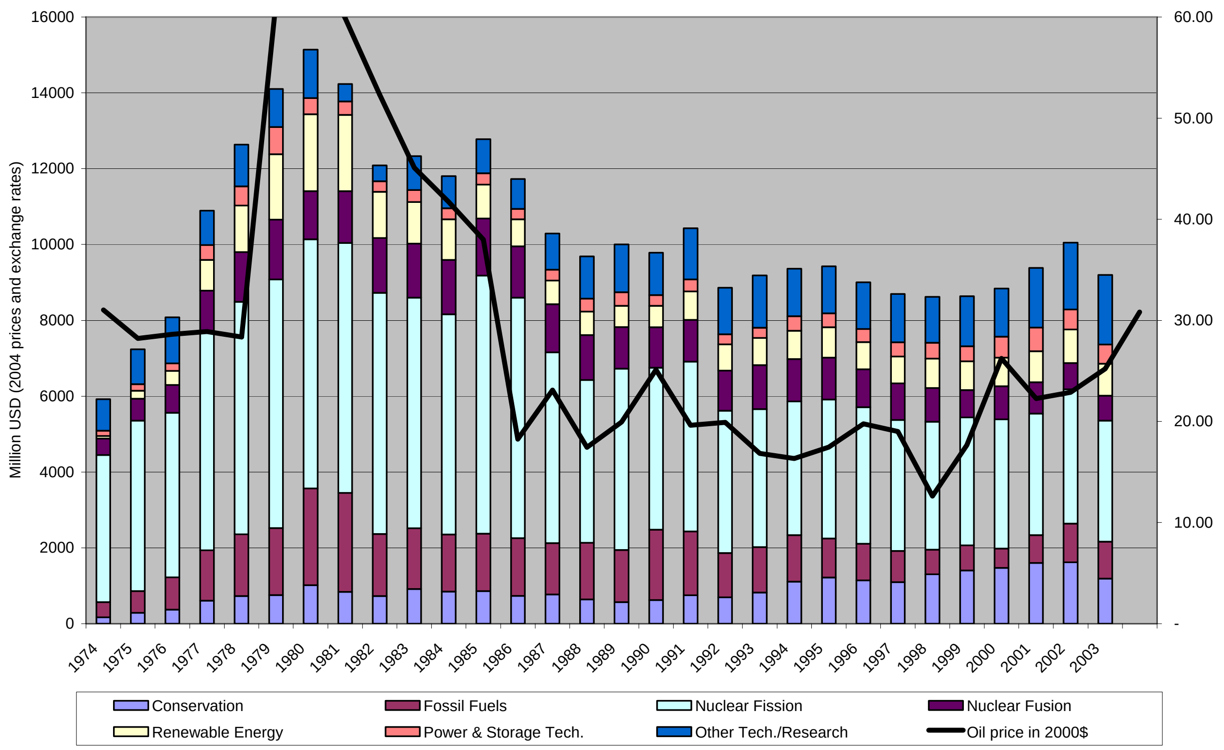
Whether we are talking about new renewable forms of energy or clean fossil fuel, there is a significant cost increment. If a negotiated limitation on emissions designed to created a 'market pull' incentive to bring these technologies on-stream is beyond realistic diplomatic possibilities, the question then arises whether 'technology push' policies can achieve the same thing. Research, development and deployment expenditures by governments are one such policy lever. This paper asks whether the current level of research and development resources marshalled behind new energy technologies is likely to bring them to market.

We simply do not know what level of investment in R&D would be needed to bring new technologies forward. We do not even have an accurate idea of how much is currently being expended. But the trends aren't encouraging.

While public budgets for R&D have been on the rise in the past decades, public expenditure on energy R&D has been declining. This decline has not been compensated by private sector expenditures which have also declined in absolute terms. If we measure R&D intensity (R&D expenditure as a percentage of total turnover) in the energy sector, the level has more than halved from an already low level as opposed to a trend of slightly rising R&D intensity in other sectors.

It is not difficult to see that these trends have been in stark contrast to the climate change challenge that seems to have become more compelling over the same period. If there is any correlation to be observed, it is one that links R&D expenditures to oil prices. At least that was the experience during the period between 1974 and 2004. It is too early to say whether recent higher oil prices will generate a new surge in R&D expenditures.

Figure B: R&D expenditure in IEA countries and oil price 1974 - 2004



This paper does not seek to draw any conclusions about where the weight of R&D expenditures should be concentrated or the absolute magnitude of resources that should be applied to energy-related R&D. The table below *(reproduced from part V)* summarises what we know about the technical and economic potential of a range of energy technologies. A key question for policy makers is whether the overall portfolio of R&D investments stated in the last column represents a good balance.

Table C: Summary of technical and economic potential

	Technical potential			R&D gap		Competitiveness Potential		Budget
	Resource availability	Energy security	Level of Carbon free supply	Technical maturity	R&D challenges for reaching full potential	Price on CO_2	No price on CO_2	Share of total public IEA R&D expenditure in 2004
Renewables								
Solar PV	+	+	+	+/-	––	+/–	–	4.0%
Solar thermal	+	+	+	+/-	0	+/–	+/-	0.9%
Bioenergy	–	0/-	0/+	+/-	–	0/+	0	2.8%
Wind	0	0/+	0/+	+	+	+	0/+	1.3%
Geothermal	–	––	0/+	+	+	+/-	0/+	0.5%
Hydro	––	–	0/+	+	+	+	+	0.3%
Nuclear								
Fission	+	+	+	+/-	–	+	+	33.3%
Fusion	+	+	+	––	––	N/A	N/A	7.6%
Fossil fuels								
Generating Efficiency	+	+	0	+	+	+	+	~10%
Substitution techn.	+	+	–	+	+	+/-	+/-	
Capture and Storage	+	N/A	+	+/-	0/+	+	––	1.1%
Hydrogen and fuel cells	N/A	+	+/-	––	––	0/-	–	~12%

Legend: + = positive; 0 = not significant positive or negative; – = negative; –– = very negative; +/- = impacts vary from positive to negative depending on technology.

This is a difficult enough question to assess at the national level. It is even harder to undertake at the global level. Yet there may be good reasons to attempt such an exercise given the rather particular issues raised by climate concerns. The classical reasons why the private sector under-invests in R&D may be stronger than normal in the energy sector. At the same time, one effect of electricity sector restructuring in favour of market forces may have tempered an enthusiasm for long term, high risk investments in new technologies, the return on which will depend on the highly uncertain development of a price of carbon. In this case, public R&D investments may be more than usually important. To this must be added that fact that the externalities from global warming are potentially large – and will affect all nations.

Given the global application of the technologies in question, there may also be good reasons to consider a higher than usual level of international co-operation. Although there seems to be a great deal of consideration going into international coordination (and we could cite the IEA implementing agreements as a best practice here), it is appropriate to ask whether there is enough effort going into real co-operation such as sharing research facilities, experience and knowledge. Furthermore, co-operation seems to be mainly technology specific (e.g. International Partnership for the Hydrogen Economy or the Carbon Sequestration Leadership Forum). Finally, co-operation between developed and developing countries on R&D seems still to be in its infancy as most R&D programs are focused on advanced technologies that seem to be of less relevance to the problems of developing countries.

Clearly R&D is not the only lever available to countries seeking to address cleaner and more secure supplies of energy. Neither are their technological 'silver bullets' available to solve energy-related problems. Improvements need to be made incrementally across a wide range of fronts including the efficiency with which energy is used in a wide range of applications and built environments, and the extent to which the true costs of energy used are priced in the marketplace. But R&D will be an important part of the policy mix.

II A FOSSIL FUTURE? ENERGY TECHNOLOGY PATHWAYS FOR THE COMING CENTURY?

1. Economic development and rising living standards throughout the 20th century have been fuelled by an abundant and affordable supply of fossil energy. The continuing growth of the world's population combined with sustained economic development, particularly in non-OECD countries implies an enormous increase in energy demand over the 21st century.

2. The International Energy Agency's (IEA) *World Energy Outlook 2005* sees energy demand in its 'business-as-usual' scenario growing by more than 50% to 2030. World primary energy consumption is increasing in this scenario from 14.2 TW in 2003 to 21.6 TW in 2030. Long term 'business-as-usual' scenarios are showing the same picture for the whole 21st century. In a similar vein, the World Energy Council's *World Energy Assessment* has primary energy consumption growing to 26 TW in 2050 and 46 TW in 2100[2].

3. Growth in energy demand of this magnitude will have direct implications for the security, affordability and environmental sustainability of the energy supply. The IEA has investigated the risks for security of supply through to 2030 in its most recent edition of the *World Energy Outlook*. Although the world's fossil resources will be sufficient over this timeframe, the world will, in the absence of policy interventions, depend more and more on the oil and gas resources of the Middle East and North Africa. The greater part of the world's remaining reserves of abundant and easily accessible oil reserves lie in this region.

4. A desire to lessen this dependency could induce a shift in policies to other energy resources. An obvious candidate would be a return to coal. At current oil prices, converting coal to liquid fuel is a competitive proposition. But the attraction of coal does not stop with the transportation sector. According to the *Financial Times* the world is on the brink of a big switch back to coal as the preferred fuel for power stations. Reported projections by Alstom, Siemens and General Electric (the world's three biggest power equipment makers) indicate that about 40 per cent of the orders for electricity turbines in the next decade will be for coal-powered units, with the share of gas-fired plants falling to between 25 and 30 per cent. This contrasts with the recent past in which gas had become the preferred fuel for 60-70 per cent of new power stations[3]. Depending on the technology used this could jeopardise the environmental sustainability of the evolving energy mix.

What's a Tera Watt?

In this paper all energy units are expressed in Tera Watts (TW). TW is a comprehensive unit of power that shows how much energy is used at any point in time. This measure is often referred to as the 'burning rate', referring to the combustion of fossil fuels. For example the world's use of around 14 TW energy in 2003 means that the world has been 'burning' on average around 14 TW at any point in time throughout 2003.

More formally a *watt* is a *unit of power* or the amount of energy per unit of time (a TW is 1,000 billion *watt)*. When paired with a unit of time the term *watt* is often used for expressing electricity consumption. For example, a kilowatt hour, is the amount of energy expended by a one kilowatt device over the course of one hour. Other commonly used units of energy consumption are 'toe' (million tons of oil equivalent) and/or Joules. The world energy consumption in 2003 was 123 000 TWh, 10 579 Mtoe and 443 billion billion Joules or 443 Exa (E) joules. The decimal system prefixes and some often used conversion equivalents can be found at the end of this paper.

5. If the world continues on its present path it will meet its rising energy demand predominantly from fossil fuels. The IEA projects that fossil fuels will meet more than 80% of the projected increase in

primary energy demand through to 2030. Beyond 2030 the dominance of fossil fuels in the energy mix is unlikely to change without additional policy. The 'business as usual' scenario of the *World Energy Assessment* predicts the share of fossil fuels from 1990 until 2100 to be more than 60%.

6. With only moderate technological development the world is unlikely to be on an environmentally sustainable growth path. In particular, CO_2 emissions from the combustion of fossil fuels would appear to be unsustainable given their contribution to global warming. Although the precise effects and consequences of large scale CO_2 emission are considered to be highly complex and uncertain there is broad agreement between scientists that there are significant risks in allowing greenhouse gas (GHG) concentrations to rise without limitation (IPCC 2001). There is, however, much less agreement on how to act.

7. Under the UN Framework Convention on Climate Change (UNFCCC) the world community has committed itself to stabilising GHG concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate system. What that level might be remains to be determined. There have been calls to aim for a concentration that would minimise the risks by limiting likely warming to no more than 2 degrees (^{o}C) (this relates to a stabilisation level of approximately 550 ppm CO^2-equivalent[4]). Even a 2 degree increase in global average temperatures could translate into significant and costly changes in regional climates[5]. Nevertheless this doubling of pre-industrial concentrations will most likely be reached before mid century[6]. Whatever a non-dangerous level might be, it seems reasonable to conclude that unconstrained growth leading to a trebling of GHG concentrations (more than 750 parts per million) would imply unacceptable environmental and economic risks.

8. If governments wanted to stabilise atmospheric CO_2 by increasing the share of energy with near zero carbon emissions, the scale of the change in the energy mix required is sobering[7]. In a business-as-usual scenario with moderate assumptions for economic growth and population development and ambitious assumptions for decreasing the energy intensity of production, the scale of the carbon-free primary energy supply needed to stabilize atmospheric CO_2 concentrations can be calculated. For example, as can be seen in table 1, stabilising CO_2 concentrations at twice the world's pre-industrial level (~ 550 ppmv) in 2050 would require the supply of approximately 15 TW of carbon-free primary energy globally. This would mean supplying carbon free energy in 2050 on a scale equivalent to the entire current supply of primary energy from fossil, nuclear and renewable primary energy resources.

Table 1. Growth Primary Energy Demand and CO_2 Concentration Levels (in ppmv)

	2003			2050	2100
Demand	*14.2 TW*			29 TW	46 TW
		CO_2 concentration levels			
Carbon-free supply	*2.8 TW*	~ 380	*750 ppmv*	~ 11 TW	~ 29 TW
			550 ppmv	~ 15 TW	~ 38 TW
			450 ppmv	~ 21 TW	~ 42 TW

Source: Hoffert et al (1998) reference scenario taken from IPCC second assessment report; IEA (2005d) for 2003 data

9. Given the simultaneous need to diversify energy resources, accommodate strongly increasing energy demand and stabilize atmospheric concentrations of GHGs, there is a stiff challenge for energy-related research & development in the coming decades. The new energy technologies needed for a secure, affordable and environmentally sustainable energy supply will not follow on automatically. The technological challenges implied by these demands will require long lead times to bridge the gap between basic science and commercial deployment.

III WHAT IS THE TECHNOLOGICAL POTENTIAL OF NEW ENERGY TECHNOLOGIES?

10. There is a large array of possible technology solutions that could improve the security and sustainability of our energy future. The different technology solutions can be conveniently clustered as follows: technologies that improve energy efficiency; technologies for renewables and nuclear energy; technologies for a cleaner use of fossil fuels; and technologies that change the way energy is distributed and consumed (energy carriers like electricity and hydrogen)[8].

11. The next section of the paper attempts to provide an assessment of the potential contribution of different technology clusters to future energy provision bearing in mind the twin challenges of supply security and environmental sustainability.

III.1 Energy efficiency

12. This paper concentrates on the energy supply side and will not touch upon the technological opportunities for increasing energy efficiency on the demand side. This is not because improving the efficiency of energy use is unimportant. Increasing energy efficiency is highly desirable both for security of supply as well as for environmental sustainability reasons. The benefits of a decreasing energy intensity of production are exponential. At the same time it is unlikely or even impossible that energy efficiency alone will do the job or even make a large contribution. There are several reasons for this.

13. In the first place, the strong forecast growth of energy demand is largely coming from countries that are in the most energy intensive phase of economic development. They are building the physical infrastructure to accommodate future growth. Secondly, higher energy efficiency tends to lead to lower operating costs of energy services leading in turn to a higher demand from consumers for these services. This rebound effect erodes the first round gains from efficiency improvements[9]. Finally, it is difficult to find substitutes for energy. Cost-effective options for increasing energy efficiency seem to be more limited than is often suggested[10].

III.2 Renewables

Solar Energy

14. Sunlight is the most abundant energy resource in the world[11]. Despite its overwhelming potential, solar power's share of primary energy supply in 2003 was less than 0.04%. The Earth intercepts, at the edge of the atmosphere and in a right angle to the sun, around 1.37 kW/m^2 of solar energy. The energy in the sunlight that reaches the surface is much less with approximately half being reflected back into space or absorbed by the atmosphere[12]. That still leaves a formidable total – more than 6000 times current consumption. The available total is less again, depending on a region's geographic position, typical weather conditions, and land availability. The solar primary energy potential for different regions is shown as a range in Table 2 taking aforementioned characteristics into account.

Table 2. Annual Solar Energy Potential (in TW)

Region	Minimum	Maximum
North America	0.9	70
Latin America and Caribbean	0.5	32
Western Europe	0.1	9
Central and Eastern Europe	0.0	1
Former Soviet Union	0.9	82
Middle East and North Africa	2.0	105
Sub-Saharan Africa	1.8	91
Pacific Asia	0.2	9
South Asia	0.2	13
Centrally planned Asia	0.5	39
Pacific OECD	0.3	22
Total	**7.5**	**474**

Source: IPCC (2001) and own calculations. Assumptions used to calculate the minimum (maximum) solar energy potential are: using horizontal collector plan (two-axis tracking collector plane) to catch the sunlight, lower (higher) assumptions for annual clear sky irradiance and average sky clearance, 1% (10%) of the unused land as accounted for in the FAO database and that can be made available for solar harvesting technologies, 15% (30%) conversion efficiency[13].

15. From this table it can be seen that if energy demand grows from around 14 TW in 2003 to 46 TW in 2100, the incoming solar radiation, could in theory, provide enough energy to satisfy this demand. At the global level resource availability doesn't seem to be an issue for solar radiation. The real issue for solar power is being able to harvest it at a cost that can make large scale deployment economically viable.

16. There are two groups of technologies for generating electricity from solar radiation: 1) photovoltaics; and 2) concentrating solar power (or solar thermal). Photovoltaic (PV) technology permits the transformation of sunlight directly into electric current and can subsequently deliver electric energy to a specific application and/or to the electric grid. Concentrating solar power (CSP) technologies capture heat via a dark absorber surface. The heat energy is subsequently carried away by a fluid circuit that is used to drive the steam turbine generator of a conventional power block. Within these two broad technology categories there are many permutations[14].

17. Current PV technologies have typical commercial module conversion efficiencies between 5% and 15% with the prospect of improvements to around 15-30% by 2030[15]. In the very long term (after 2030) new conversion principles and concepts could lead to module efficiencies of 20-40%. The range is the consequence of different optimization approaches between cost and efficiency[16]. Solar thermal has conversion efficiencies between 10% and 30%[17].

18. While PV technologies can also make use of indirect radiation, solar concentrating technologies rely on direct radiation and are therefore mainly suitable for regions with many hours of sunlight a year (sub-tropical, and desert areas). The potential for sunbelt regions will not only be higher because of the higher solar radiation but also because they are more conducive to the use of technologies with a higher efficiency (solar concentrating technologies). The advantage of PV systems is that they are flexible and modular and can be implemented on virtually any scale and size, connected to the grid or used stand alone. The advantage of CSP technologies is that they can be integrated into conventional thermal plants.

19. Solar heating and cooling systems make direct use of the heat of the sun without first generating electricity. They comprise technologies and designs for solar water heating, space heating and cooling. The estimated capacity today worldwide is 0,09 TW. The IEA estimates that these systems would eventually be

able to provide 5% to 10% of the overall low-temperature heat demand in IEA countries (0.0025 TW – 0.005 TW).

20. Although pure solar radiation is a CO_2 free energy source, and its theoretical potential for CO_2 reduction is large, solar conversion technologies are not CO_2 free. PV implies a rather large amount of embedded CO_2 emissions because the production of solar cells is energy intensive and may imply heavy use of fossil fuels in producing them. The energy payback time - that is the amount of time needed for a PV system to harness the equivalent energy expended in its production - used to be longer than the life time of the system. But payback times are now between 2 and 8 years while they are expected to decline further to between 1 and 2 years within the next 10 years. On average, a solar concentrating power application has an energy payback time of less than 1.5 years and a 25 year lifetime[18].

Bio-energy

21. Bio-energy is the energy derived from all organic material from plants, trees and crops and from municipal and industrial waste streams. It is very diverse and provides for three different energy sectors: electricity, heat and transport. Due to its widespread non-commercial use (e.g. wood gathering) in developing countries, solid biomass is the largest 'renewable' energy source[19] and represents 10.3% of the world total primary energy supply[20]. In some of the world's poorest countries in Africa, bio-energy is the most important energy resource and is used mainly for cooking, space heating and lighting. Modern use of bio-energy is around 15% of the total bio-energy supply of 1.6 TW in 2000[21].

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Solar energy conversion technologies are mature technologies and already commercially viable in niche markets such as off-grid use in rural areas. Wider scale commercial use will require further cost reductions. R&D efforts should be focused on: (1) reducing material consumption; (2) increasing conversion efficiency; and (3) optimising manufacturing. Further deployment is necessary to benefit from 'riding the learning curve' but technological breakthroughs are also necessary for large scale deployment of photovoltaics. CSP technologies are closer to large scale commercialisation in sun-belt areas.

22. Biomass has a low energy density that ranges from only 0.01 W/m^2 for burning wood through to a maximum 1.2 W/m^2 for intensively managed tree plantations[22]. By comparison, fossil fuels used for thermal generation of electricity have energy densities ranging between 1,000 and 10,000 W/m^2. This low energy density of biomass means that land use is the most important factor of production for bio-energy. When assessing the technical potential of bio-energy, assumptions must be made as to the availability of land (given competing land uses), and the quality of the land for crop production. Fischer and Heilig (1998) calculate the maximum available area that could potentially be used for the production of bio-energy feedstock, taking into account land needed for feeding the growing world population[23]. In their view, any claims on land for food production are likely to be minimal on account of some rather ambitious assumptions about the potential for improved productivity in food production systems.

23. However, it is not realistic to assume that all unused and untouched land is available for bio-energy crop production since the damage this would cause to remaining un-modified ecosystems and biodiversity is unlikely to be acceptable. Furthermore, transport distances, water availability, and the need for fertilisers will further constrain the area of land realistically available for the production of bio-energy feedstocks. Although it is extremely difficult to assess the extent of these limitations, we assume that valuable forest and wetland is not available for bio-energy feedstocks production[24]. On this basis we set out in table 3 sets our estimate of the land that is potentially available for additional bio-energy feedstocks.

Table 3. Annual Bio-energy Potential

Region	***Maximum additional area for biomass***	***Max additional area biomass minus forest and wetland***	**Additional technical potential bio energy**
	Gha	***Gha***	***TW***
North America	0.04*	0.01	0.08
Latin America and Caribbean	0.67	0.33	1.79
Western Europe	0.01*	0.00	0.01
Central and Eastern Europe	0.01*	0.00	0.02
Former Soviet Union	0.03*	0.01	0.05
Middle East and North Africa	0.05	0.04	0.20
Sub-Saharan Africa	0.42	0.15	0.80
Pacific Asia	0.02	0.00	0.02
South Asia	0.01	0.01	0.06
China			0.06
Pacific OECD	0.01*	0.00	0.03
Total	**1.27**	**0.57**	**3.13**
Total Earth land surface	*14.9*	*14.9*	

Source: WEA (2000), Fischer and Heilig (1998), Nakicenovic, Grubler and Mc Donald (1998). The productivity of a crop will be between 1 and 30 of dry tonnes a hectare a year. While the net energy value of a ton will be between 10 and 20 Gigajoules a ton[25]. To calculate the energy potential the WEA uses the normal productivity of a perennial crop (8.5 oven dry tonnes per Gha a year and subsequently 20 GJ per oven dry ton). * The estimate for the developed world in Fisher and Heilig has been divided proportionally to the relative surface area and are therefore just a very crude indicator for the relative distribution. For the total potential this does not make a difference.

24. In addition to biomass from growing crops, biomass can also be derived from municipal solid waste. There is no detailed data on the potential for municipal waste but the World Energy Assessment states that this could be as much as 0.19 TW for the world[26].

25. Traditional biomass combustion for heat and power uses fully mature technologies. Modern bio-energy technologies can follow many complex and competing conversion processes (combustion, gasification, fermentation, pyrolysis, anaerobic digestion) from raw materials to heat, electricity and fuels. Electricity production from biomass based on steam cycles is proven technology.

26. Conversion efficiencies can be maximised by co-generation of heat, electricity and fuel so as to maximise the benefit per unit of mass/volume of biomass. This could raise electricity production efficiencies from 25% to 35% currently, to as high as 40% to 50%[27]. In locations where waste heat can be harnessed to a productive use, combined heat and power plants can further increase combined efficiency to 60% or even up to 80%. These biomass integrated gas turbine systems are well advanced but are still expensive and not yet commercially viable.

27. An advantage of bio-energy is that it is the only renewable energy source that can presently be produced as solid, liquid or gaseous fuels and can therefore substitute and complement fossil fuels in the short term without requiring major end use equipment modifications. This holds in particular for the use of bio-fuels in vehicles. Firstly, sugar cane ethanol in Brazil is a proven and commercial technology although production costs differ widely between regions. Secondly, lignocellulosic ethanol has possibly more long term potential because it makes lower demands on the need for fertilizers and pesticides and can also be produced from residues of agricultural crops thereby reducing competition for the use of land between farmers and energy producers. Nevertheless the technology is not proven and needs further research and

development. Finally there is bio-diesel produced from vegetable oils and animal fats. Its long term potential is limited given its relatively high costs without much room for improvement.

28. Furthermore, the life cycle costs of bio-energy are not always very favourable because of the energy and water needed to grow feedstock together with the potential for nitrate pollution of groundwater and soil phosphate saturation. There are also consequences for biodiversity and landscape values. The energy costs of producing and transporting feedstock are typically around 5% of the energy value. This has been taken into account when calculating the technical potential.

Wind

29. Wind energy resources depend on a region's mean wind speed and its frequency distribution. Wind resources can be exploited in areas where wind power density is at least 400 watts per square metre at 30 metres above the ground[28]. Wind energy produced 0.5% of total primary energy supply in 2003.

30. In table 4 we have taken the estimate of the technical global energy potential from the *World Energy Assessment*. For this it was assumed that about 27% of the earth's land surface is exposed to a high enough wind speed and that for practical reasons only 4% of the potentially available land could be used. This is derived from detailed studies for the Netherlands and the US taking into account siting constraints such as valuable forest, inaccessible mountain areas and social, environmental and land-use constraints.

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The assessment of the potential for bio-energy technologies is mixed. On the one hand the potential of existing proven bio-energy technologies is limited – though currently under-exploited - because of the very low energy density of bio-fuel crops. This low density implies the need for large areas of land and, in many cases, intense irrigation and fertilizers damaging the water and nitrogen cycles. The cost of producing and transporting the feedstock provides a floor to the cost structure of bio energy and makes it difficult to improve its competitiveness. On the other hand the enormous potential of biotechnology solutions using the natural diversity of microbes and microbial communities was stressed. The genetic modification of feed stocks is still in its infancy and requires more long term basic science.

The bio-energy R&D challenges for power generation and vehicle fuels should focus primarily on increasing crop productivity. Furthermore the need for more R&D on 2nd generation bio-fuels that increase possible blending with petrol to 50% or even higher was stressed.

31. In addition to these siting constraints, wind energy is variable so there are real limits to the share of total energy demand it can meet[29]. Off-shore wind sites should also be taken into account when assessing the technical potential of wind as an energy resource. Resources off-shore are much larger than those onshore, but to be viable they have to be close to transmission infrastructure. There are no global detailed assessments available for the off-shore technical potential. A study by Germanische Lloyd and Garrad Hassan & Partners states that approximately 0.34 TW could be generated in the coastal areas of the European Union[30]. This is approximately two thirds of the onshore (land) potential.

Table 4. Annual Technical Potential Wind, Geothermal and Hydro Energy

Region	*Wind energy resources (< 4% land used)#*	*Geothermal**	Hydro
	TW	*TW*	*TW*
North America	1.90	0.58	0.10
Latin America and Caribbean	0.79	0.58	0.14
Western Europe	0.51	0.16	0.09
Eastern Europe and former Soviet Union	1.65	0.52	0.10
Middle East and North Africa	0.60	0.13	0.01
Sub-Saharan Africa	0.54	0.38	0.15
Pacific Asia	1.01	0.25	0.02
central and south Asia	0.06	0.25	0.01
China	0.25	0.29	0.15
Total	**7.32**	**3.15**	**0.80**

Source: WEA (2000)# The 4% estimate comes from detailed studies of wind power potential in the Netherlands and the United States (WEA 2000). * The Global Technical Potential for Geothermal electricity is based on estimates taken from Steffánson (1998) and Gawell, Reed and Wright (1999).

32. Wind technology has become as reliable as more traditional energy sources with turbines having a design life of 20 years or more. Variability and grid reliability together with public concerns about the acceptability of siting turbines limit the further development of wind energy. However, recent developments in electricity market reform, which promote better grid integration and improved management of natural cycles of renewables, diminish the technological barriers that have constrained market penetration. Nevertheless the variability of wind and its often remote or offshore locations will always put pressure on the requirements for transmission, storage and load management[31]. To optimize the use of wind power (and other renewables such as photovoltaics) the existing electricity networks have to be 're-engineered' to manage the loads[32].

Geothermal

33. Geothermal energy is energy available as heat emitted from within the Earth, usually in the form of hot water or steam. Geothermal resources have been identified in more than 80 countries while there is recorded utilisation in 71 countries[33]. Its use is mainly concentrated along active tectonic plate boundaries where volcanic activity transports high temperature molten material to the near surface. Geothermal energy accounted for 0.4% of the total primary energy supply in 2003.

34. Resource availability estimates display a very wide range. Some studies take the total heat flow through the continental crust as an energy resource that could potentially be harvested while others take into account today's conversion techniques and only consider the accessible resources[34]. The latter more realistic approach is taken in this paper. For example, Gawell, Reed and Wright (1999) state that conversion techniques could tap at best about 0.07 TW of electricity-generating capacity and enhanced recovery and drilling improvements currently under development could enlarge this total to about 0.138 TW[35]. However Stefánsson estimated the worldwide technical potential for geothermal electricity at about 3 TW[36]. For our purpose we take the latter higher estimate.

35. Besides electricity production, geothermal energy can also be used in the supply of heat. The direct use of geothermal energy is approximately 0.001 TW of installed capacity[37]. If we assume that the direct use of geothermal energy is in the same ratio to its technical accessible potential as for geothermal electricity, its technical resource potential would be 0.15 TW. The total technical accessible geothermal

resource availability would in that case be approximately 3.15 TW. The largest shares of this potential are along the tectonically active Pacific margins of North, Central and South America and Asia.

36. Unlike most renewables, geothermal power is not a variable energy resource but can operate 24 hours per day, providing base-load capacity. Use of geothermal energy for electricity and direct heat applications is a mature technology which is limited to locations with certain geo-tectonic characteristics. But there is also the possibility of using lower temperature geothermal energy at far greater depths of the earth by using geothermal heat pumps. This can theoretically be done virtually anywhere on Earth but this technology is in its infancy. Limited growth is foreseen in geothermal energy supply because of the very long project development times and the high risks and cost of exploratory drilling[38].

Hydro

37. Hydro energy uses running water to turn turbines that generate electricity. Hydropower is a well established, mature technology and by far the largest renewable resource for electricity generation, producing 0.47 TW or 2.2% of total primary energy supply in 2003.

38. The principal constraint on hydro power's technical potential is competing land uses, particularly in the case of large hydro schemes that need large dams. Limited public acceptance of large hydro power plants with high environmental and human impact means that the remaining untapped potential may not be that large. The technical potential reported in table 4 takes social, environmental, geological and technical evaluations into account[39]. As hydroelectricity is estimated to be close to saturation, 0.8 TW seems to be a reasonable assessment of its technical potential.

39. Hydropower is an extremely flexible technology from the perspective of power grid operation because of it's built in energy storage and short reaction time.

III.3 Nuclear

40. Nuclear energy could in theory provide an abundant energy resource for electricity generation that avoids the emissions associated with fossil fuels. Furthermore, resource availability doesn't pose serious limitations to the production of nuclear energy for the coming century. This can be seen in Table 5 where the resource availability estimated by the *World Energy Assessment* is presented based on data from the NEA and IAEA. The distinction between reserves and resources is based on the price for which the uranium could be extracted. Furthermore if a new technology (fast breeder reactors) were to be used this could increase the potential energy available from nuclear fission 30 times[40].

Table 5. Uranium Resource Availability

in tonnes of uranium (unless otherwise indicated)	Reserves* < $130 / kgU	Resources* < $130 / kgU	Speculative Resource*	Total In TW Conventional reactors	Total In TW Fastbreeder reactors
North America	11.9	1.7	59.7	73.3	406.7
Latin America and Caribbean	2.9	2.3	21.4	26.5	796.1
Western Europe	0.9	0.8	2.7	4.5	134.1
Central and Eastern Europe	0.2	0.3	3.8	4.3	128.9
Former SU	13.6	7.0	33.6	54.2	1626.7
Middle East and North Africa	0.9	0.9	0.9	2.6	78.8
Sub-Saharan Africa	11.2	4.0	22.3	37.6	1128.8
Pacific Asia	0.1	0.0	0.2	0.3	9.5
South Asia	0.7	0.4	0.5	1.6	48.6
Centrally planned Asia	1.5	0.7	28.2	30.4	912.7
Pacific OECD	13.0	6.8	0.0	19.8	594.9
Total	56.9	24.9	173.4	255.3	7657.8

Source: NEA and IAEA (2005). Calculated from the amount in tonnes of uranium, assuming 1 tonne = 544 terajoules and for fastbreeder reactors 1 tonne = 16 320 terajoules. Uranium from seawater or other fissile materials such as thorium are not included. * In the NEA/IAEA (2005) publication reserves are officially referred to as Reasonably Assured Resources, Resources are Inferred Resources and speculative resources are Undiscovered Resources.

41. If all electricity was produced by conventional nuclear reactors (and electricity demand was to stay stable) there would be enough for the next 41 years without taking speculative resources into account. Adding these would increase the resource life to 99 years. If there was a shift to fast breeder reactors, then the resource could be made to last for centuries or even longer.

42. At the moment there are 443 nuclear power plants in operation that produced in 2003 approximately 0.9 TW of nuclear electricity and heat (6.5% of total primary energy supply). If nuclear energy were to retain its share of total global energy supply through to 2050, it would imply an increase in production capacity from approximately 1 TW in 2003 to 2 TW in 2050 (energy demand will approximately double). This would mean that in addition to replacing existing plants - that will reach the end of their designed life over the next 45 years – there would have to be new additional capacity constructed of about the same size. If commissioned on a steady basis, this would imply opening 18 new nuclear power each year through to 2050 (800 new plants). The current rate of construction is far below this level, although in the mid 1980s a construction rate of around 30 reactors was achieved. There are presently 26 nuclear power plants under construction, each with a construction time of several years. The IAEA

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Nuclear energy is considered a mature competitive and reliable energy source. The light water reactors used at the moment in most countries have the disadvantage of using only a small part of the uranium input and therefore produce a relatively large amount of waste for each unit of energy generated. R&D efforts should focus on waste management and on the more efficient use of uranium - in fast breeder (Generation IV) reactors .
Development of fast breeder nuclear power plants is expensive and will take decades. Commercial use of the first fast reactors is not foreseen before 2030. Although safety issues could technically be overcome and the risks of a severe incident could be reduced to very minimal proportions, the main obstacle will most likely remain overcoming negative public opinion.

Fusion is potentially a competitive, safe, sustainable and abundant energy resource, but is many years from fruition. The scientific concept is proven, but its technical feasibility is not. The objective of the International Thermonuclear Experimental Reactor (ITER) project is to demonstrate the technological feasibility of fusion power. If everything works out according to plan, a demonstration plant will open around 2035. ITER is an expensive ($5 billion over 10 years for the first phase) and high risk project, but also one that has a potentially high payoff.

estimates that 60 new nuclear plants will be constructed in the next 15 years. On this basis, nuclear power faces a formidable challenge even to maintain its current 6.5% share of the energy mix.

III.4 Clean fossil fuels

43. The technical potential for fossil fuels to improve energy security in a way that is consistent with environmental sustainability depends on technology and innovation. Three inter-linked options are in play here:

- technologies that make it possible to substitute between fossil fuels so as to decrease dependence on oil;
- technologies that enable a switch to cleaner and more efficient use of fossil fuels;
- and technologies that could render fossil fuels emission free through the capture and storage of carbon dioxide.

Resource availability

44. It is by now broadly accepted that there is no shortage of fossil fuel resources. Estimates of conventional and unconventional oil, gas and coal resources indicate there is more than enough to meet likely energy demands for the coming century. (See table 6, taken from the World Energy Assessment, 2000) The total available conventional resource of 1057 TW compares with current annual demand of 14.2 TW in 2003 that is projected to grow to 46 TW by the end of the century. If unconventional resources are taken into account the world could rely on fossil fuels for at least 800 years with an annual demand of 46 TW.

45. Because fossil fuels are highly fungible and can be substituted for each other it isn't necessary to adapt existing energy infrastructure in a massive way if one was to become scarce or there was a desire to decrease dependence on one of them for energy security reasons. Coal, gas and oil can all be converted to liquids, gas and solids. The relative significance of each fuel will be determined by the relative supply costs of each fuel for differing end-uses. When the convertibility of fossil fuels is taken into account, there is no supply shortage. Viewed from this perspective, dependence on Middle East diminishes as a problem.

Table 6. Fossil Fuel Resources (in TW a year*)

in TW a year	Coal		oil		Natural Gas	
	conventional	unconventional	conventional	unconventional	conventional	unconventional
North America	192	813	6	379	12	136
Latin America and Caribbean	17	36	25	114	14	17
Western Europe	37	323	3	9	10	22
Central and Eastern Europe	24	111	0	1	1	7
Former SU	158	3508	11	45	82	198
Middle East and North Africa	0	2	132	139	71	74
Sub-Saharan Africa	46	168	5	5	5	8
Pacific Asia	0	11	2	7	7	16
South Asia	51	79	1	1	2	4
Centrally planned Asia	74	431	7	8	2	77
Pacific OECD	55	191	1	49	3	16
Total	**655 [3.4]**	**5675**	**194 [4.8]**	**757**	**207 [3.0]**	**576**

* The numbers indicate the amount of TW that could be burnt in one year. For example the conventional coal resource in North America is 192 TW. This means it would be possible to burn 192 in TW for one year before the resource is depleted. If you would burn 2 TW on average

throughout the year, this would mean that the coal resource would be depleted in 96 years (192/2). The number in brackets in the last row illustrates the amount in TW the world was burning for coal, oil respectively natural gas in 2003. Source: WEA (2000). For coal and oil total reserves and resources are shown; using for conventional oil WEC 1998 estimates; and for unconventional oil total resources from enhanced oil recovery, oil shale and tar sands estimate from WEC 1998 and for heavy crude oil the estimate from Meyer 1997; for conventional natural gas the total recoverable reserve estimate from WEC, 1998; and for unconventional gas total recoverable resources from enhanced recovery, coalbed methane, tight formation gas. Estimates for gashydrates and geopressured gas are not shown in the graph. The unconventional natural gas estimate would otherwise be more than 30 000 TW.

Substitution and high efficiency technologies

46. The technology that converts coal, biomass and gas into liquid synfuels is a mature technology – the so called Fischer-Tropsch process that has been used in South Africa by Sasol since 1955. If oil were to run out, making liquid fuel from coal and gas would be an obvious candidate to fill the gap, as would conversion of tar to synthetic crude oil. According to an article in the *Financial Times* (6 March 2006) the technology to produce liquids from natural gas will be tested on a commercial scale in Qatar this year when the largest plant constructed so far opens there. The Oryx Gas-To-Liquids plant is a joint venture between Sasol and Qatar Petroleum. Another option would be to obtain methane from methane hydrates liquid, although this option is far from market commercialization.

47. Secondly, there is also considerable potential for new energy technologies that increase the efficiency of the energy conversion process. This would both reduce harmful emissions and energy dependency because less resource is needed to produce the same amount of electricity, heat and liquid carbon fuels.

48. The efficiency in a combined cycle power plant is enhanced because the steam from combustion of the fossil fuel (both natural gas and coal) is used twice, first to drive a gas turbine then to drive a steam turbine. The best plants that use coal as an input can increase efficiency up to as high as 55%. Plants that use natural gas can increase efficiency even further to almost 60%. This should be compared to the efficiency of a traditional electricity plant of approximately 35%[41]. Further gains can be made if usable heat can be captured directly for domestic ("district heating") or industrial heating purposes. This can increase efficiency to beyond 80%. These technologies are proven and already implemented in new commercial power plants.

Carbon Dioxide Capture and Storage (CCS)

49. Capture and storage of carbon dioxide from fossil fuel conversion processes raises the possibility of a very strong reduction in emissions, the principal drawback of reliance on fossil fuels. Although capture of CO_2 seems to be more challenging from a technology perspective, the potential of capture and storage technologies is in the end determined by the availability of storage options.

50. The main options for carbon storage (besides natural sinks) are underground injection into geological formations, disposal in oceans and chemical fixation of CO_2 as a solid carbonate. The last two options are still in the research phase and have not been tested in demonstration projects.

51. CO_2 storage in underground reservoirs has already been put into practice on a commercial basis for enhanced oil recovery. Storage in geological formations uses many of the same technologies. The IPCC has investigated the potential availability of suitable storage locations and their proximity to major industrial and urban areas where the large point sources of CO_2 are located[42]. Its conclusion is that in most cases these locations are within 300 km of one another contributing to the workability of this option. The number of reservoirs that qualify for CO_2 storage and their capacity requires more careful study. Preliminary research suggests that there is sufficient capacity for several decades but beyond this there will be difficulties in accommodating all the CO_2 that is likely to be produced[43]. Others state that there is potentially enough capacity to store all the fossil fuels still in the ground[44].

52. Disposal of CO_2 in oceans is effectively an attempt to short-circuit the normal cycle in which around 70 percent of emitted CO_2 will eventually find its way into the ocean. As long as the atmosphere remains in chemical equilibrium with the ocean, the injected CO_2 will stay in the ocean indefinitely. But if not, it will return to the atmosphere[45]. Lackner and Sachs (2006) conclude that the environmental impact of ocean storage combined with short storage times makes ocean storage an option of last resort, and not a very attractive one[46].

53. Finally, CO_2 could be converted by a chemical reaction into solid carbonates. This is a permanent, safe and proven way to store the CO2. However the mining operations to provide the raw material (minerals) needed for the reaction would be very large. In addition, the reaction time is still very long and the technology to improve this is still in its infancy. Finally, the costs of the reaction process are very high and there is a lower boundary to costs because mining and handling the carbonates are mature technologies with little room for improvement.

54. Before it can be stored, CO_2 must be captured and transported. Transport does not pose major new technical challenges, but does create infrastructure investment needs. The most logical place to capture CO_2 is at large point sources such as power plants, cement plants, refineries etc. Emissions from other sources such as the transport, agriculture and residential sectors are too dispersed to make capture viable. There is a wide range of technologies used to capture CO_2. Several are already mature and well understood[47]. They have been used, for example, in industrial processes to produce hydrogen.

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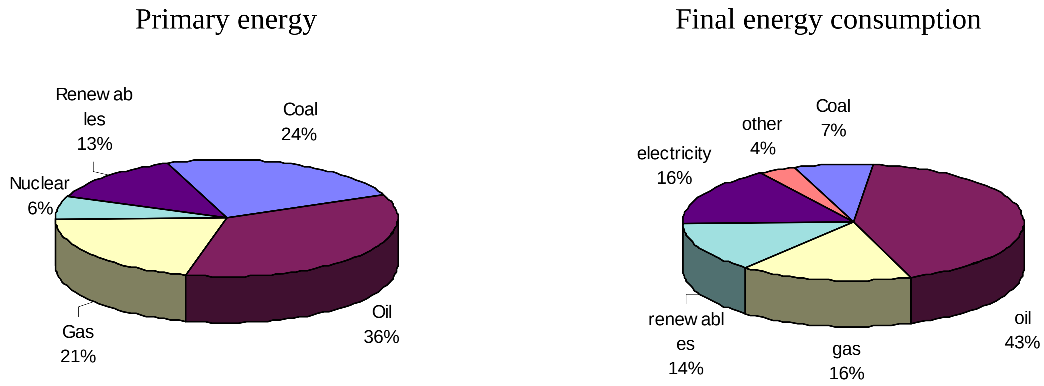
The technologies to capture, transport and store CO_2 are mature and well understood. Nevertheless it will take at least until 2015-2020 before CCS technology for power plants will reach the required scale.
The first R&D challenge is to demonstrate the technology on a larger scale and search for the most cost effective and safe technology option. Secondly there is a need to better understand and validate the permanence of underground storage in various geological formations. Public R&D should focus on developing quantified measures that can be used to certify the suitability of potential storage sites. CCS cannot be widely deployed before there is an accepted means of verification that is resistant to a huge economic incentive to cheat.

II.5 Energy carriers

55. An adequate assessment of the potential of new energy technologies needs to take into account the complete ‘energy value chain’, from primary energy until its end use in buildings, transportation and production processes.

Figure 1 Primary Energy and Final Energy Consumption in 2003



Source: IEA Key World Energy Statistics

56. An important characteristic of most alternatives to fossil fuels - such as nuclear and most renewables - is that they must be transformed to electricity or another energy carrier before they can be put to use and consumed. Although electricity is growing in importance, in 2003 it still accounted for only 16% of final energy consumption. At the moment electricity is limited primarily to users connected to

grids. This excludes alternatives for fossil fuels – except biofuels – from important parts of the energy end use market, in particular, the transportation sector. At the same time it explains the attractiveness and enthusiasm for biofuels and hydrogen as these could possibly both allow for the use of energy derived from nuclear and renewable sources in the transportation sector. In this way, both security of supply and concerns about greenhouse gas emissions could be addressed.

57. To assess the importance of this it should be recalled that the energy sector is globally responsible for more than 60% of all GHG emissions. In Annex 1 countries, for which more precise data is available, the transport sector is responsible for 21% of total GHG emissions (26% of total final energy consumption representing roughly 3.7 TW in 2003) [48]. As the transportation sector and the demand for liquid fuels are set to grow in all likely energy scenarios, the importance of a carbon-free transportation fuel will be increasing in the coming decades from an environmental point of view. The scale of the forecast is such that there will not be sufficient bio-energy to service even the transport sector as the maximum additional amount of bio-energy that can be achieved is probably close to 3 TW, less than current consumption. From a security of supply perspective, an alternative to oil would bring a welcome decrease in dependence on Middle Eastern oil – a dependence that is forecast to grow even more pronounced.

Hydrogen and fuel cells

58. Hydrogen is a clear and odourless gas that can be oxidised into water, releasing energy and water vapour in the process. It is effectively a zero-emission energy carrier if produced directly from renewable or nuclear energy, or from natural gas and coal with CO2 capture and storage. If hydrogen is produced by water electrolysis, the emissions will depend on the upstream process to produce electricity[49]. Like electricity hydrogen can be produced from all primary energy sources[50] making it attractive from a security of supply point of view, but unlike electricity, hydrogen can be stored in liquid, solid or gaseous form.

59. The main technical advantage of hydrogen is that it can be used in almost all stationary and mobile energy applications. It can potentially be used in powering vehicles, running turbines, generating heat and electricity for buildings and in fuel cells to generate electricity. According to the IEA, fuel cells are the technology of choice to exploit the full benefits of hydrogen in terms of energy security, emissions and efficiency[51]. The efficiency of hydrogen fuel cell vehicles is at least twice that of ordinary vehicles with internal combustion engines. In addition, hydrogen fuel cell vehicles reduce local environmental pollution since the only emission is water vapor.

60. Storage, however, is a problem because of the low energy density of hydrogen. Compressed hydrogen storage appears to be the most likely solution although liquid hydrogen or metal hydride storage is also possible. Another major barrier is the infrastructure adjustments that would be needed for hydrogen to be reticulated on a large scale.

III.6 Conclusion technical potential of new energy technologies

61. To conclude this discussion of the technical potential of new energy technologies, we briefly summarise the contributions each could make to the twin challenges of improving security of supply and minimising environmental impacts.

Security of supply

62. From a political point of view security of supply is often understood as guaranteeing a stable supply of energy at an 'affordable' price, under all circumstances[52]. For an adequate assessment of security of supply we should take into account

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The production of hydrogen and applications of fuel cells are both mature technologies. They are likely to first find application in niche stationary applications. Their highly touted use in transportation vehicles is only in the pilot phase and significant R&D efforts are needed to improve performance and reduce cost. This holds in particular for the storage of hydrogen in vehicles. Although most R&D programmes are on target, technological breakthroughs, e.g. fuel cell materials and solid hydrogen storage, are needed for the technology to become viable for mass production. The technology is further constrained by both the marginal cost of fossil fuels and the existing energy infrastructure that is not suitable for fuelling a hydrogen-based transportation system.

(among other factors) the concentration of market suppliers, the political stability of the supply regions, market liquidity and system reliability[53]. Any such assessment should be analysed separately for the oil, gas, coal and electricity markets taking into account all relevant parameters at country or even regional level (witness the California electricity crisis).

63. In this paper we take a longer term perspective and assume substitutability of energy resources to a large extent. As a proxy for long term energy security we look at the availability of energy resources in regions in combination with projected final energy demand to assess the risk of concentration of energy market suppliers in specific regions[54].

Table 7. Renewables and Geopolitical Energy Security

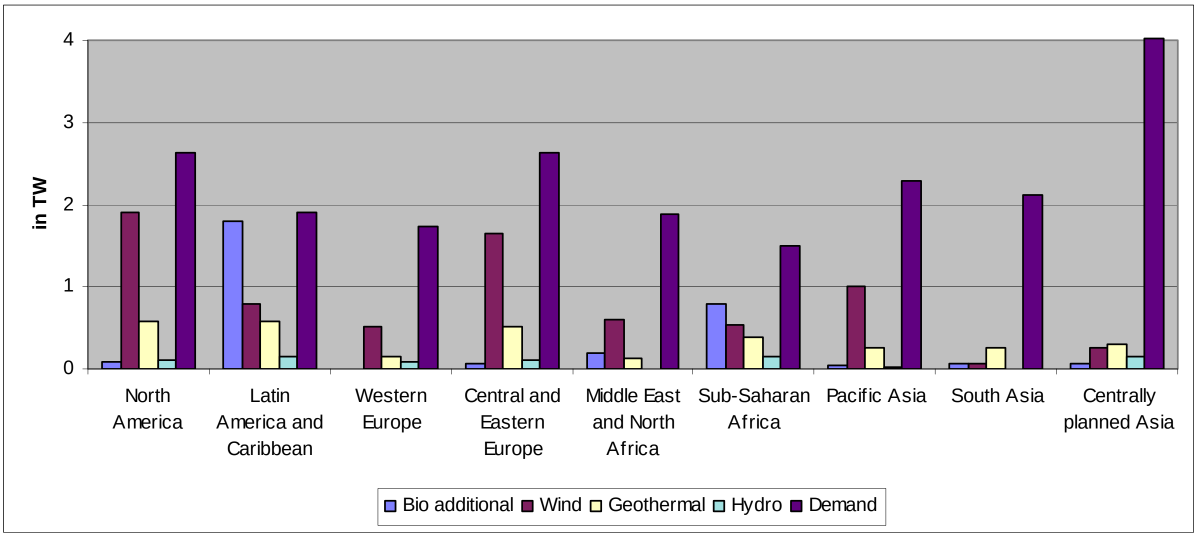
In TW	Primary Energy Supply Renewables		Demand**	Supply / Demand	
	Incl Solar*	Excl Solar	2050	Incl solar	Excl. solar
North America	38.7	2.7	2.6	14.6	1.0
Latin America and Caribbean	19.3	3.3	1.9	10.2	1.7
Western Europe	4.8	0.8	1.7	2.7	0.4
Central and Eastern Europe***	45.3	2.3	2.6	17.2	0.9
Middle East and North Africa	54.9	0.9	1.9	29.0	0.5
Sub-Saharan Africa	47.9	1.9	1.5	31.9	1.2
Pacific Asia	6.3	1.3	2.3	2.8	0.6
South Asia	6.4	0.4	2.1	3.0	0.2
Centrally planned Asia	20.8	0.8	4.0	5.2	0.2
Total	**255.4**	**14.3**	**29.0**	**8.8**	**0.5**

* For solar we take the average of the calculated range ** Total primary energy demand as in IPCC 2001 and geographical distribution from Nakicenovic et al (1998) *** Including all the countries of the former Soviet Union

64. Table 7 calculates ratios for import dependency considering the technical potential for renewables in different world regions. As the table highlights, in theory, there is sufficient renewable energy potentially available to meet the energy needs of all regions in 2050, without having to import energy. The picture is however strongly skewed by the abundance of solar energy in all regions of the world. In theory, solar power outstrips demand by several orders of magnitude. Without large scale direct solar energy, the potential for renewables to meet energy demand is much less. In that case four regions will depend for more than 50% of their energy demand on outside regions or other energy sources (a value of < 0.5 in column 8 in figure X): Western Europe, Asia and even the Middle East and North Africa. Total supply from renewables will only be enough to meet 50% of total energy demand.

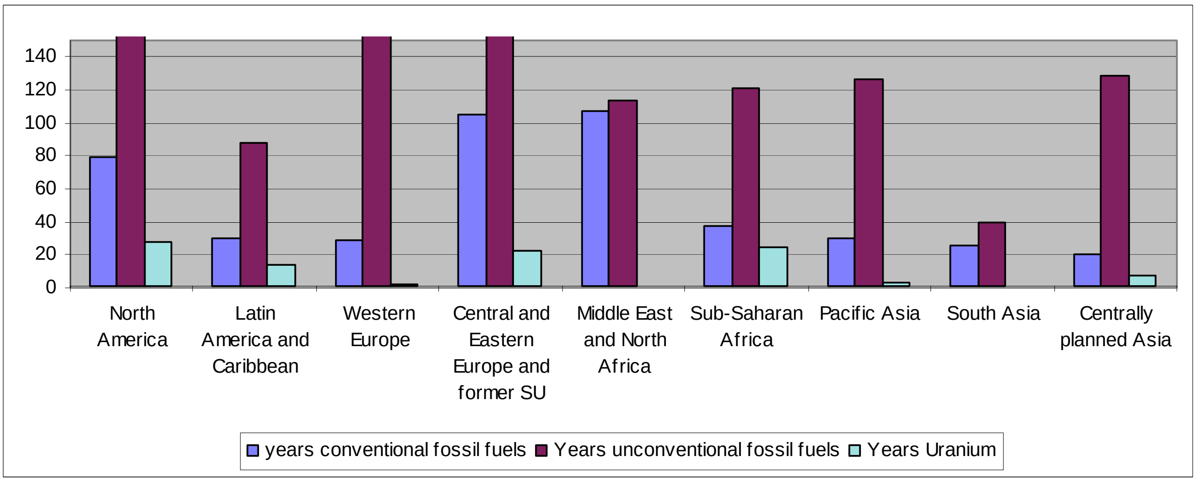
65. The distribution of the renewable energy sources excluding solar energy is also shown graphically in figure 2 below. In North America, wind energy could for example provide a potentially large energy resource whereas in South America bio-energy potential stands out in the region's projected energy demand. In any case, for all renewables, together or separately, the respective market concentration of the energy resource is not very high.

Figure 2 Resource Availability and Projected Demand for Renewables (Excluding Solar)



66. To get a better idea about the magnitude and distribution of fossil and nuclear energy resources in relation to demand we need to draw up a slightly different picture because these resources are obviously non-renewable. In figure 3 we show the conventional and unconventional fossil fuels and uranium resources as a ratio of demand in different world regions. In this way the picture shows the number of years before the resource will be depleted in different regions if energy demand were to be at 2050 levels from now on and was to be met only by using these respective resources. Clearly, this is only useful for broadly comparative purposes.

Figure 3 Numbers of years before depletion (fossil and uranium resources / divided by projected 2050 demand in the region)



Source: Conventional and unconventional fossil resources as defined in paragraph II.1.4. For presentational reasons the unconventional fossil fuel resources have been topped off at 150 years (they get as high as 1470 years for Central – and Eastern Europe and the former Soviet Union). Conventional oil resources are also shown separately by way of illustration. All resource levels have been divided by the total primary energy supply foreseen in 2050. In reality demand will of course gradually grow over the years and demand will be met by a mix of energy resources and the number of years will therefore be longer as projected in the figure.

67. Most analysis of security of supply focuses on the oil, gas and coal markets separately. Nevertheless when the fungibility between fossil fuels is taken into account, reliance on Middle East and North-African oil is much less pronounced, in particular when unconventional resources are taken into

consideration. In the latter case there is no strong concentration of resources and no region is dependent on other regions for the coming century if the costs of extraction and refining are left to one side. As energy security is a stable supply of energy at an 'affordable' price, we will turn separately to the question of cost, below (part IV).

Environmental sustainability

68. With respect to environmental sustainability, the potential amount of carbon-free supply needs to be taken into account. For renewables and nuclear this is simply determined by the resource availability as these are zero emission resources whereas for fossil fuels the potential for carbon-free supply is ultimately determined by the CO_2 storage capacity.

69. To stabilise the atmospheric CO_2 concentration at 550 ppmv (~ warming of 2^o Celsius) and at the same time accommodate increasing energy demand the world needs 15 TW carbon-free energy supply in 2050 and 38 TW in 2100. Given total primary energy consumption of 14.2 TW in 2003 (of which just 2.8 TW comes from carbon-free sources) the requirements are daunting. Although the world will almost certainly rely on an energy mix instead of just one 'silver bullet' technology or resource, it is clear that bio-energy, wind, geothermal and hydro alone will collectively not be enough to realise the need for carbon-free energy as their combined technical potential is not more than 14 TW.

70. Solar energy is a special case. In theory it could provide sufficient energy indefinitely as our estimate of the technical potential for the world is as high as 245 TW annually. As an illustration, Lackner and Sachs (2005) note that a 1000-km^2 field of solar panels (an area equivalent to 10 percent of the Sahara) would gather roughly twice the current global energy consumption if they operated at 10 percent efficiency, the level of efficiency already achievable today. However, all the PV cells shipped from 1982 to 1998 would only cover approximately 3 km^2 and PV solar energy represented only 0.039% of global primary energy supply in 2003. A massive scale-up would be required to achieve the level of carbon-free energy supply needed.

71. Nuclear energy has a large potential but as we have seen in table 6, resources are too small to support a world energy infrastructure predominantly based on conventional nuclear power. The world's uranium resources would be depleted in a matter of a few decades if all energy were to be supplied by conventional reactors. Furthermore, to supply more than 10 TW from conventional nuclear plants by mid century would mean a massive construction programme.

72. The alternative would be to move toward fast breeder reactors, a different technology generation that increases potential energy from nuclear by approximately 60 times and therefore removes all concerns over resource limitation for the coming century. However, breeder technologies increase the risk of proliferation of fissile materials suitable for use in nuclear weapons. This is an important technical and political constraint. In addition, it must be noted that all nuclear energy generates waste that poses storage challenges on timeframes well beyond anything we have experience in managing. This too raises a powerful source of political concern. Finally fast breeder reactors need extensive R&D programmes to achieve the required scale up for commercial plants.

73. That leaves the capture and storage of CO2 from the on-going use of fossil fuels. The advantage is that the technology exists, no large changes in our energy infrastructure are necessary, there are no resources limitations on a century scale and the storage possibilities seem to be sufficient. The capture and storage/sequestration technology is proven and could make use of fossil fuels a practically zero emissions technology.

74. Timing is the most important issue for capture and storage. To reach the required capacity to stabilize atmospheric concentration in time we should be able to capture, transport and store the total CO_2 emissions the world emits because of its energy use. To illustrate the magnitude of the challenge Ken

Caldeira uses the following example. At the moment there is only one commercial scale capture and storage project, the Sleipner site in Norway where approximately 270 000 tC is stored a year. To generate sufficient carbon-free energy to stabilize CO_2 concentrations (~550 ppmv) we would need to build roughly 2 Sleipner plants per day for the next fifty years[55].

IV WHAT IS THE ECONOMIC POTENTIAL OF NEW ENERGY TECHNOLOGIES?

75. Although the technical potential of several alternative energy resources is substantial (this holds in particular for solar and nuclear power) more than 80% of the world's energy needs are derived from fossil fuels. This is because fossil fuels are abundant, relatively inexpensive and easy to use and likely to remain so for decades to come. Alternative energy resources and applications therefore have to compete with fossil fuels to gain wider deployment and market share[56].

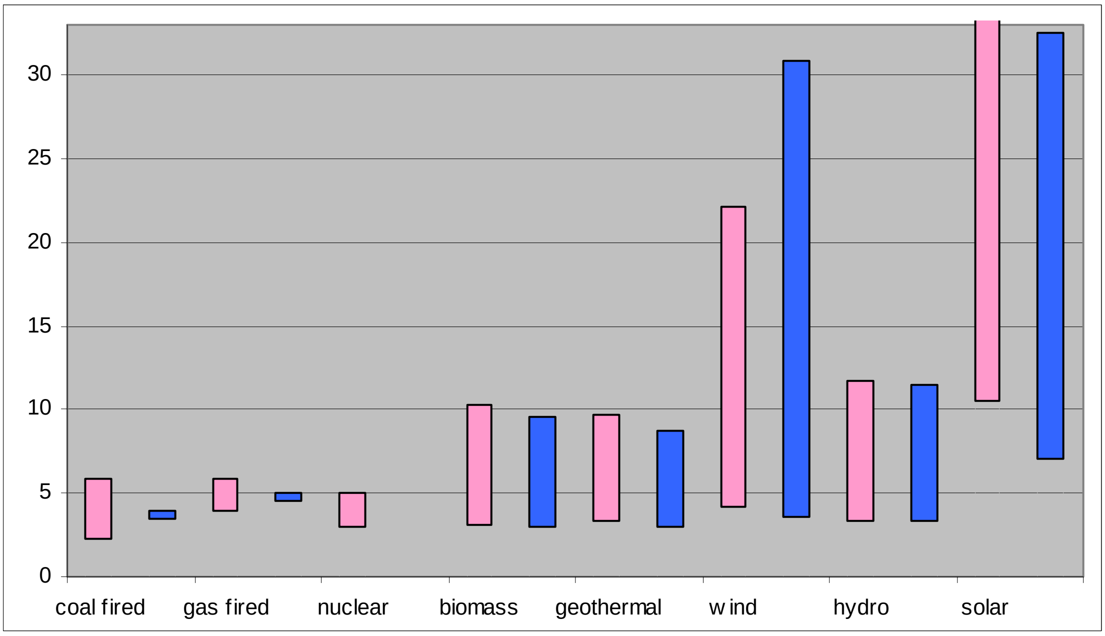
76. Because energy is used in many different ways, we have to take into consideration the different forms in which energy is distributed and consumed. In general a distinction can be made between energy use that could in theory be grid-connected and mobile use of energy, primarily in the transportation sector. Electricity is the reference modality for the former while hydrocarbons are the reference modality for the latter.

IV.1 Electricity generation costs

77. The relative economic attractiveness of electricity generating technologies can be demonstrated by comparing 'current' and potential cost per kWh. The estimates of 'current' electricity generating cost per kWh are as presented in the IEA *Energy Technology Perspectives* (2006) report. The estimates are based on an IEA/NEA (2005) study that has collected data for more than 130 state-of the-art-power plants that are currently under construction (to be connected to the grid from 2010 onwards), shown as the pink (light) bar in figure 4[57].

78. Substantial cost reductions in the past few decades have made a number of renewable energy technologies competitive with fossil fuel technologies, but only in certain applications and regions. Making renewable technologies competitive on a large scale requires further technology development and market deployments. Economies of scale and economies of learning will bring down the costs when deployment increases. The IEA *Energy Technology Perspectives* has made assessments of the cost potential of the different technologies. The projections for 2030 are reported in blue (dark) in figure 4.

Figure 4 Electricity generation cost 'present' (pink/light) and potential (blue/dark) in $cents / kWh



Source: IEA (2006) Based on standardised lifetime cost approach; economic lifetime is 30-40 years, using 10% discount rate. Cost of solar technologies have been topped of for 'current' electricity generation cost because of presentational reasons. IEA/NEA (2005) and IEA (2006) give a far more in-dept comparison of the electricity generation cost and the potential for cost reductions for the different technologies.

79. Hydroelectricity is a cost effective energy source. But it is also a mature technology and it will be difficult to increase its capacity much further. New hydroelectricity plants need to take into account high capital costs whereas existing hydro plants are often fully depreciated. Wider deployment of wind power is likely to see costs fall and become competitive with fossil fuel power plants in several locations although wind energy needs to be substantially cheaper than power sources that are not variable in nature and can be dispatched whenever they are needed. Geothermal energy will, without some technological breakthrough, only be competitive in a few places where the earth's heat is easily accessible at high enough temperatures.

80. The cost of solar power has been decreasing rapidly though the experience curves seem to fall short of those seen in the computer industry. Lackner notes that, given the similarity to computer equipment, it seems that there are issues other than technical factors that prevent prices in the photovoltaics industry from following a similarly steep decline. For solar electricity to become interesting other than in niche markets a cost improvement by about a factor of 20 to 30 would be required. Given the low density of solar power, a photovoltaic panel generating on average 1 kW of electricity requires between 20 m^2 and 50 m^2 of collector surface. A 100 kW combustion engine fits under the hood of a car. Lackner notes that it is therefore difficult to see how the costs of solar power could come down enough although he states as well that there is no obvious hard limit that would prevent such cost reductions.

81. Nuclear generation could play an important role and the costs of nuclear energy seem to be very competitive at the moment. Nevertheless the full costs of nuclear power plants are often debated as some energy experts state that the real costs are higher than reported. On this view these costs would need to come down to make nuclear energy competitive without any implicit government support and taking into account a more appropriate discount rate and project size[58]. Furthermore the estimated electricity generating costs seem to differ in different studies.

82. From an economic point of view, fossil fuel electricity plants, especially Combined Cycle Gas Turbines, are very often the technology of choice because of their low overall cost. However, even if the

cleanest and most efficient clean-coal power or gas production technologies were to become commercially available and replace existing power plants in the coming years, the reduction of CO_2 emissions would probably be around 15 per cent in 2020[59]. While this would be a very significant achievement in itself, it must be set against a baseline scenario in which absolute emission levels are still rising and will continue to do so, only at a slower pace. Secondly, without a price on carbon, coal based power plants are likely to become the lowest-cost electricity suppliers again.

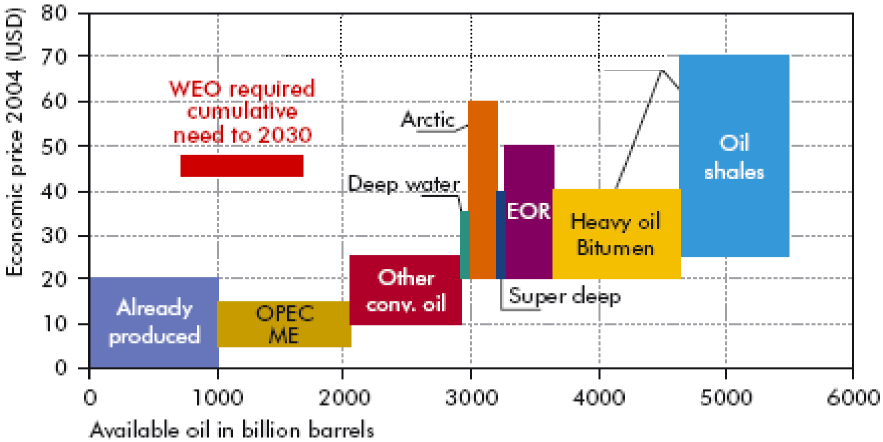
83. If fossil-fuel based energy generation is to be environmentally sustainable, carbon capture and storage technology is needed to render fossil fuels an (almost complete) carbon free energy source. The problem with the technology is that it always comes at a premium to electricity generation from fossil fuels without capture and storage. CCS would increase electricity production costs by 2-3 $cents/kWh. By 2030, these costs could fall to 1-2 $cents/kWh. This should be compared with the future costs of other carbon free energy sources. In many cases CCS will still be less expensive than renewables and maybe even nuclear energy. Put another way, carbon mitigation could well be the leastcost solution. In the absence of a carbon price, zero-carbon emissions technology is unlikely to come on-stream without public funding for the experimental scale-up of alternative CCS strategies.

IV.2 Projected costs of alternative transportation fuels

84. The commercialisation and large scale use of alternatives to the transportation fuels used presently (gasoline, diesel, LPG) depends on the price developments of these fuels and the projected costs of developing alternatives. The expansion of substitutes for the current mix of transportation fuels, mainly based on oil refinery products, is a matter of sufficiently high oil prices. Nevertheless, it is a misperception that this will automatically price cleaner alternatives into the market. It is also not true that alternatives can prevent short term price fluctuations from happening because the development of alternatives and market introduction is a *lengthy* process. Nevertheless the prospect of alternatives to conventional oil sources entering the market has in itself a moderating effect on oil prices in that it reduces the incentive for oil producers to collaborate to raise prices and puts a brake on undesirable market concentrations. Notwithstanding that, market manipulation by low cost producers will always remain something to wary about.

85. Most alternatives that are immediately ready for the market (non-conventional oil, Gas-to-Liquid, Coal-to-Liquid and Liquefied Natural Gas) are all based on fossil fuels and therefore no solution to the climate change challenge. Recent research indicates that substantial additions to conventional oil can be brought on stream at a full production cost of less than $20 per barrel while unconventional oil from oil sands has a full production cost of about $25. Synthetic substitutes for refined petroleum products produced from natural gas or coal are cost effective when oil prices are in the $25 - $40 per barrel range. While these costs are in 2004 prices, and in the meantime the costs of production and exploration have gone up, the conclusion remains the same. There are several alternatives for conventional oil that will enter the market when the price of oil is expected to remain high.

Figure 5 Oil cost curve, including technological progress: availability of oil resources as a function of economic price



Source IEA (2004b): The x axis represents cumulative accessible oil. The y axis represents the price at which each type of resource becomes economical

86. Hydrogen and bio-fuels are two obvious alternatives that can make a contribution to both supply security and climate change. Hydrogen is presently far from being competitive and much more technological development is needed to remove obstacles for large scale use in vehicles. Bio-fuels are also limited by cost considerations and, more importantly, suffer from very low energy density and high land use. The price of ethanol ranges from \$30 a barrel in Brazil to around \$90 in Europe. Ethanol from lignocellulosic conversion is around \$120 a barrel whereas bio-diesel is in the \$90 to \$170 a barrel range. These costs can certainly be reduced but are unlikely to come down to levels competing with fossil alternatives on any large scale if there is no price for carbon.

87. The CO_2 emissions of fuels must be split into emissions during the use of the vehicle and upstream emissions from refining the feedstock. Unfortunately for oil fuels, emissions during vehicle use are the most significant fraction and cannot easily be captured and stored. Nevertheless, the use of capture and storage should be considered for the production stage of all oil, gas, coal and biomass based fuels. This could be a cost effective way to reduce carbon emissions. But again, without regulation or a government imposed carbon price, carbon capture and storage will not be a commercially viable option.

IV.3 The likely succession of technologies given known cost differentials

88. An assessment of the economics of different technological options leads to the conclusion that without policy changes, cost differentials will favour fossil fuels for decades to come.

89. Many worry about an approaching production peak for crude oil and the increasing concentration of affordable conventional reserves in fewer and fewer countries with significant consequences for security of supplies[60]. However as we have seen, concerns over security of supply are not likely to induce a move away from fossil fuels. While it may indeed be the case that in the coming decades cheap oil supplies will become more and more concentrated in the Middle East, this doesn't hold for fossil fuel resources in general. These are very large and widely distributed. Running out of oil is not the same as running out of fossil fuels and it is also not the same as running out of relatively 'cheap' and abundant supplies of fossil fuels.

90. Although a great deal of attention is given to security of supply concerns, markets should be able to find adequate responses when working properly. This is not to deny an oversight and regulatory capacity to make sure markets are indeed functioning properly. For example: making sure there is adequate interconnectedness, fighting abuse of market power and preventing dominant market concentrations by mergers and acquisitions. Furthermore, R&D directed to new technologies is beneficial from an energy security of supply point of view as it will smooth the transition from conventional to unconventional technologies and resources.

91. Market forces seem less equipped to respond to the environmental challenges that are a consequence of increasing CO_2 emissions. Given the cost differentials, the most likely response of the market is to move to alternative fossil fuels as a backstop technology for oil. Because mitigation efforts to prevent emissions are not priced by the markets, the private sector will not automatically invest in carbon-free technologies.

92. However even if governments could collectively agree on an adequate world wide pricing mechanism for carbon, private sector investments in developing new technologies would still likely fall short. The main reason for this is that innovators are often unable to protect their new knowledge against third parties and that this problem may be more pronounced in the energy generation sector than other industrial sectors. Empirical research suggests that these knowledge spillovers are quite large, both within and between countries[61]. This means, for example, that even if all countries could agree on a credible cap and trade system for carbon dioxide it is socially beneficial for governments to invest in R&D for carbon-free energy technologies to help bring down the economic cost of meeting the emissions caps. Getting the prices right is of enormous importance but not the end of the story.

93. If carbon is <u>not</u> priced through government regulation, R&D investments in carbon-free energy technologies become even more important. But without any technological or social breakthrough in solar or nuclear technologies, the R&D investment is unlikely to lead to adequate results as ‘clean’ fossil fuel technologies will almost always (except for enhanced oil recovery) be more expensive than conventional fossil fuel technologies.

94. At the same time, as soon as the cost of clean technologies becomes acceptable it is more likely that international agreement can be reached on a policy that limits emissions. The conclusion must be that market incentives and regulation that place a price on carbon and innovation policy are two sides of the same coin to tackle global warming in the most cost effective way.

V R&D PRIORITIES AND PROGRAMMES FOR ENERGY TECHNOLOGIES

95. For well described reasons, the private sector under-invests in R&D relative to the public benefits that could be realized from such investments. Firstly, the private sector is unable to appropriate the full benefits of its investments because of knowledge spill-overs. Secondly externalities such as air pollution are not priced in the market thereby undermining any incentive to internalise them. Furthermore the long term and/or high risk nature of some investments may diminish the level of R&D[62]. These possible market failures could in particular hold true for the energy sector. The externalities from global warming are potentially immense. And at the same time the restructuring of the electricity sector in favour of market forces could temper enthusiasm for long term, high risk investments in new technologies, the return on which will depend on the highly uncertain development of a price of carbon.

96. This section focuses mainly on R&D expenditure to bring on-stream new energy technologies. Using R&D expenditure as an indicator for the capacity to innovate can be criticised, not least because it

measures inputs instead of results. Moreover, R&D is only one of the inputs determining the highly complex innovation process[63]. Nevertheless, R&D intensity (R&D expenditure over total production) is often used in economic analysis as an innovation indicator for good reasons. Numerous econometric studies have demonstrated a quantifiable relation between R&D intensity and technological development measured by total factor productivity[64]. Furthermore, empirical studies often find a strong relation between R&D expenditure and output indicators such as the number of related patents[65]. The levels and rates of growth of R&D expenditure are therefore viewed as reliable indicators of innovative capacity. A more pragmatic reason is that data on output indicators such as commercial successes from innovation or the diffusion and adoption of technological advances are difficult to quantify[66].

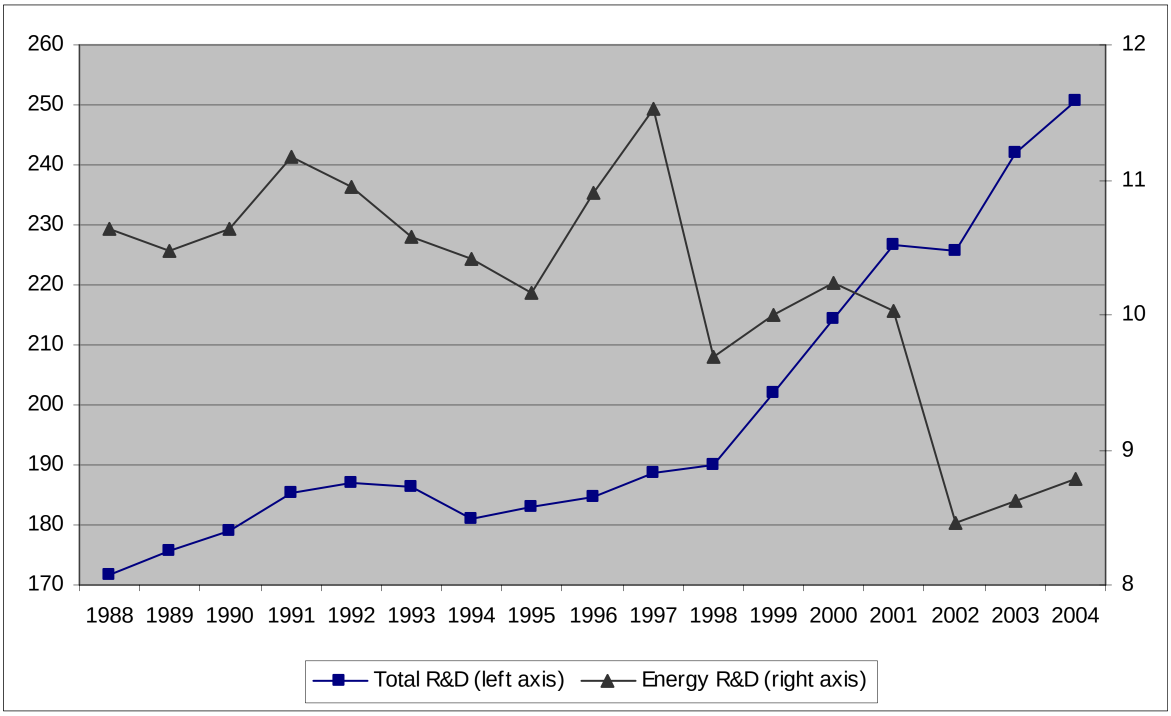
97. Research and Development activities are funded and performed by many organizations, the most important being firms, universities and government laboratories and research institutions. The main funder and performer of R&D in industrial economies is generally the private sector. More than one-half of all OECD R&D expenditure is financed by companies, and they perform two-thirds of all R&D activities[67].

98. Statistics on energy R&D are notoriously difficult to find and interpret[68]. In fact a wide array of activities can be seen as energy R&D although it is not their primary focus. This holds for example for military R&D or basic research into catalyst and materials science, both of which can have a clear energy spin-off. These are not classified as energy R&D but do contribute to energy innovations. The same sort of difficulty exists with private R&D data because these are normally organised by industrial branches rather than by expenditure type[69].

V.1 Public energy R&D

99. In most industrialized countries, total public R&D expenditure in general has increased in real terms whereas at the same time energy R&D expenditure has been declining quite dramatically from the peak levels of the early 1980s (figure 6). Since GDP has been growing in real terms, energy R&D expenditure as a percentage of GDP has been declining even more rapidly. This means we are spending a smaller and small share of our total income on researching new energy technologies and solutions. Total public energy R&D expenditures in OECD countries amounted in 2004 to approximately $ 9 billion.

Figure 6 Development public R&D expenditure in OECD countries (total R&D and energy R&D) (in constant 2004 billion USD and PPP)



Source: OECD R&D database, March 2006. Total public energy R&D differs from the data in the IEA database because in the OECD R&D database Basic Research is included whereas demonstration projects are excluded and secondly because the group of countries included in the database slightly differs.

100. The decline in energy R&D expenditure from the peak in 1984 until 2003 was especially pronounced in the United Kingdom (-95%), Spain (-85%), Germany (-73%), Italy (-63%) and France (-55%). These sharp declines have not been matched by an increase in research by the EU on a collaborative basis. Although in constant 2004 USD the total EU research programme has been steadily increasing from approximately $ 1.9 billion a year in the First Framework Program (1984 – 1987) to $ 3.8 billion a year in the Sixth Framework Program (2002 – 2006), the energy share in the budget has been declining in both percentage and absolute terms.

101. The energy budget declined from $ 0.9 billion (1984 – 1987) to $0.5 billion (2002 – 2006) annually. In the Commission proposal for the Seventh Framework Program (2007 – 2013) the energy R&D budget is set to double to approximately $1 billion a year. This would bring energy R&D funded through the EU budget back to just above its 1984 levels in real terms.

102. The federal governments of the United States and Japan are the dominant public sector supporters of energy R&D, currently and historically. The combined funding of the U.S. and Japanese governments is around 70% of the total energy R&D expenditure of all IEA countries ($ 6.8 billion in 2004). Measured as a percentage of GDP, energy R&D investments in the US ranks fifth among IEA countries, while Japan ranks first.

Table 8. Aggregate Percentage Change in 11 major IEA Energy R&D Program Areas

	1974 - 2003		1990 – 2003	
	All	w/o US, Japan	All	w/o US, Japan
Conservation	- 20%	- 42%	+ 88%	- 36%
Fossil	- 78%	- 77%	- 68%	- 64%
Renewable	- 75%	- 56%	- 5%	- 14%
Nuclear	- 91%	- 83%	- 88%	- 63%
Total	- 65%	- 80%	- 53%	- 65%

Source: Runci, Paul, Energy R&D Investment patterns in IEA countries, PNNL, October 2005, based on IEA R&D database[70]

Historically, nuclear energy R&D programs have accounted for a majority of public sector expenditure on energy R&D in IEA countries (around 50% until 1997 and decreasing to around 40% thereafter). At the same time nuclear fission programs have also experienced the largest declines since the early 1980s. The perceived risks of nuclear technologies and waste management, and the availability of cheaper and easier options for power production made siting, permitting, and financing new nuclear plants exceptionally difficult. Japan is the only industrialized country in which current funding levels exceed those of the early 1980s. Expenditure on fusion R&D has been roughly 20% of total nuclear R&D since 1992 ($ 700 million in 2004; the ITER project will cost around $ 600 million a year).

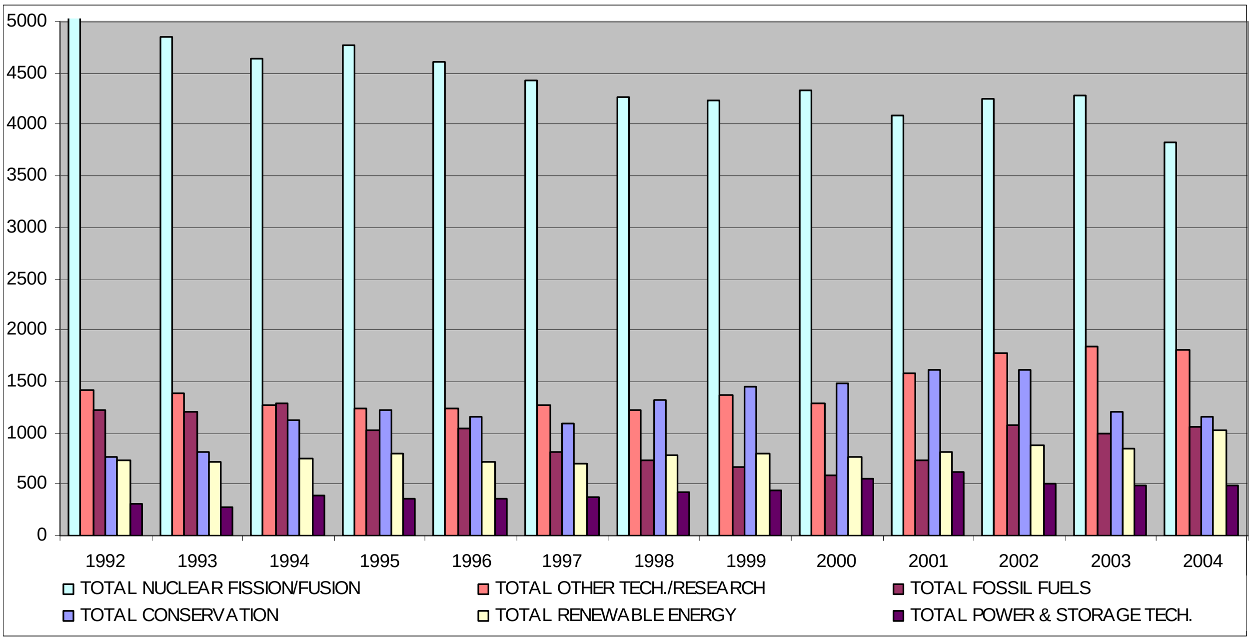
103. With the exception of Australia, fossil programs (around 10% of the total) declined slowly in most countries and rapidly in some countries, notably the UK, Germany and Japan. In recent years coal conversion has seen an increase in R&D funding to roughly $100 million because of the increasing interest in capture and storage technologies[71]. Total fossil fuel R&D amounted to roughly $1 billion in 2004.

104. As total government energy R&D budgets have contracted, resources have become more concentrated on what are perceived to be next generation energy technologies: renewables and energy conservation (including energy efficiency). Although from 1990 to 2003 R&D expenditure on renewables showed a small decline in most IEA countries, budgets have been on the rise since 1992 . The renewables share of the portfolio has grown from 8% in 1992 to 11% in 2004. The total R&D expenditure on renewables of approximately $1bn in 2004 has been concentrated on solar ($500 million), bio-energy ($261 million) and wind energy ($122 million).

105. Budgets for power and storage technologies have been rising as well, from around $300 million in 1992 to $500 million in 2004. As these R&D programmes are often related to variability problems and grid management issues they benefit the development of renewables as well. Conservation R&D is the only item that has seen a very rapid increase from 1990 onwards, almost doubling its claim on resources to around $1.1 billion in 2004.

106. Research and development in hydrogen and fuel cells has taken off rapidly since 2000. Total public spending in OECD countries in 2004 was approximately $1 billion and represented some 12% of all public energy R&D spending. The investments of the private sector in hydrogen and fuel cells are even more significant at around $4 billion in 2004[72].

Figure 7 Public R&D expenditure by program area in IEA countries (in millions constant 2004 USD)



Source: IEA database

Public energy R&D in selected non-IEA countries

107. Data for non-IEA countries is very limited. There is no systematic collection and reporting and therefore this picture is drawn on the basis of anecdotal collected information. These numbers should therefore be treated with caution. In developing countries energy R&D is often financed through development assistance programmes. Non-nuclear R&D programmes have a different nature compared to R&D programs in IEA countries and focus often on improving energy access in rural areas. The biggest donors of energy R&D programmes in developing countries are the US (DOE), EU (CORDIS) and Japan. Among non-IEA member countries Russia, China and Brazil have some of the most interesting energy Research and Development programmes.

108. **Russia** has large fossil fuels resources and its energy R&D is focused on fossil fuels and nuclear power. In recent years Russia has also started projects on alternatives like hydrogen, fuel cells and renewables[73] although in monetary terms these programmes are small compared to the fossil and especially nuclear R&D programs. For example in 2005-2006 the Russian government's hydrogen program is $15 million[74] whereas nuclear R&D programmes (including programmes improving safety of reactor sites) add up to approximately 1.2 billion a year[75].

109. **China** has set ambitious targets to meet its future energy demand. Besides increased energy conservation and efficiency China is actively deploying renewable energy technologies, increasing its nuclear capacity and developing advanced fossil fuel technologies.

110. Government public spending on renewable energy deployment has been concentrating on hydropower (among others the $25 billion Three Gorges dam project), rural energy programs ($5 billion over several years in biogas, small hydropower, solar cookers etc)[76] and in recent years research into fuel cells and hydrogen (around $120 million in 2001 – 2005)[77]. Furthermore, the World Watch Institute reported in May 2006 that China invested, excluding large Hydro, $6 billion in renewable energy in 2005 out of a world total of $38 billion. Since 2001, the government has invested about $40 million in R&D

related to clean-coal technologies[78]. Finally, the state owned Chinese Energy Conservation Investment Corporation invested $ 2.4 billion in modern biomass in 2001-2005.

111. Utilising flows of foreign investments in Clean Development Mechanism (CDM) projects brings $1 billion to China each year[79]. At the same time, over the last decade international donors such as the Global Environmental Facility, the US Department of Energy and the Asian Development Bank have invested in renewable energy and energy efficiency projects at a level of approximately $2 billion a year.

112. **Brazil**'s approach to the treatment of research and development provides a particularly interesting case study. After reforming its electricity sector in the 1990s, Brazil established new regulations to define investment in energy efficiency and R&D. It was established by law that 1% of the annual net revenues of the privatised utilities had to be invested in energy efficiency and R&D. Roughly 50% of this was channelled through a public benefit research fund (CTEnerg Fund) to make sure societal interest were sufficiently addressed. The total R&D expenditure of CTEnerg amounted in 2004 to around $45 million[80].

113. The **Ukraine** government has developed, in cooperation with the World Bank and other international donors, several projects in the wake of its 1998 *National Plan on Climate Change* [81]. The focus of this plan is mainly on energy conservation and efficiency ($1.2 billion funded by government, industry and international donors over three years) and the development of the coal industry ($315 million funded by the World Bank[82]). In 2004 government public spending on energy R&D was roughly $6 million, primarily for the development of nuclear energy.

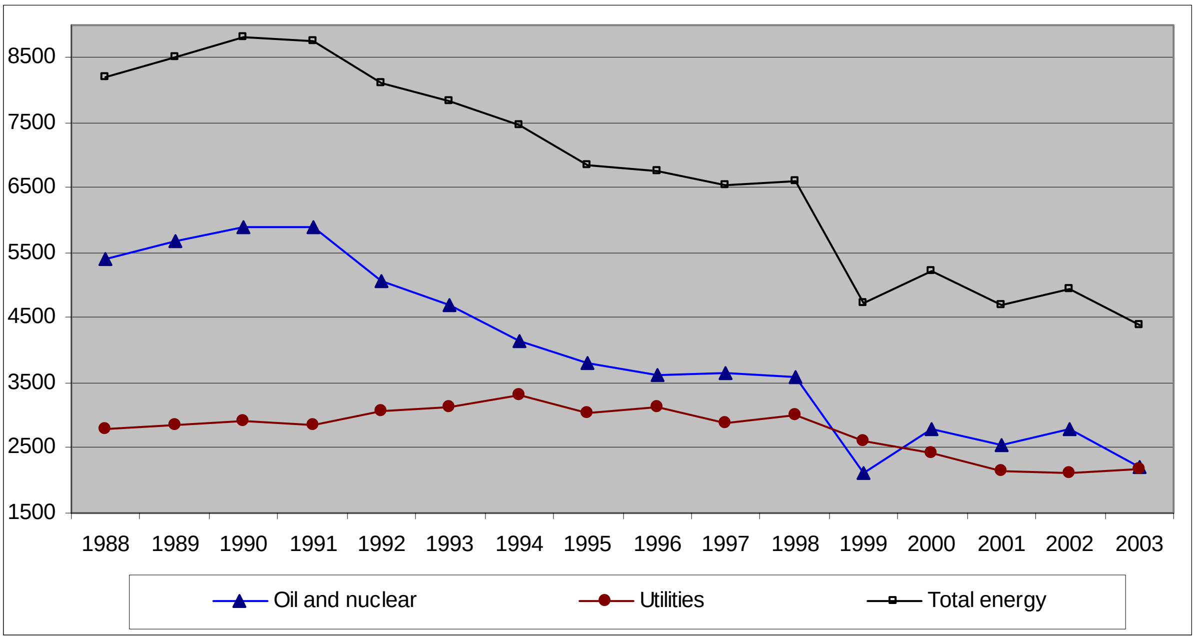
V.2 Private Energy R&D

114. The data on private energy R&D investments is more limited because it is reported only at the level of industry classifications. This means it doesn't allow for a breakdown of the type of energy R&D by programme area.

115. Private industry data on energy R&D shows a declining trend similar to that witnessed in the public sector. In constant 2004 USD, energy R&D in industry has declined from around $8.5 billion at the end of the 1980s to around $4.5 billion in 2003. Unlike other sectors, energy R&D is mainly financed by governments and the available data suggests that private R&D investments range between 40 – 60% of government energy R&D expenditure.

116. From the large non-OECD countries, data is available for Russia detailing expenditure in 2003 of about $53 million in constant 2004 US dollars whereas in 2000, Chinese companies spent $1.4 billion (around 28% of the total energy R&D expenditure of the by companies in OECD countries represented in figure 8).

Figure 8 Energy R&D Expenditure by Industry in OECD countries (In Millions Constant 2004 USD PPP)



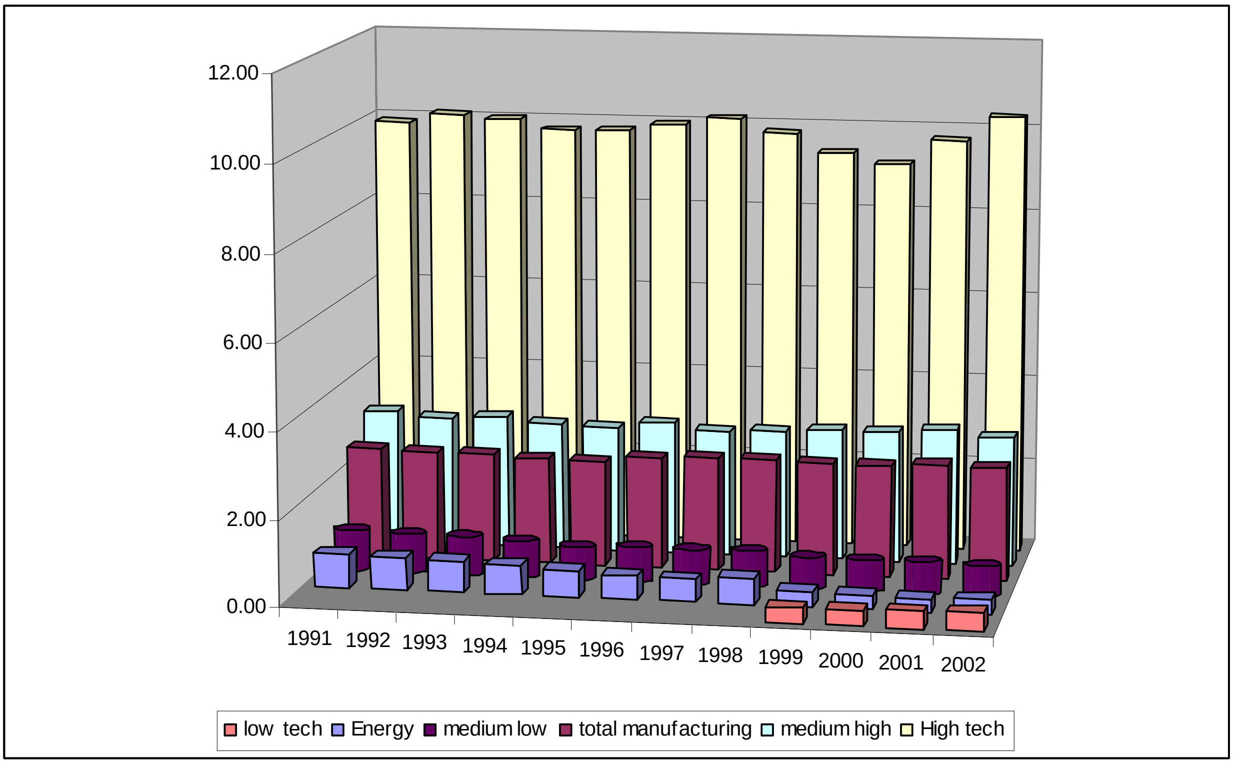
Source: OECD, EAS (ANBERD database), March 2005[83]. Missing years are estimated by implying industry average growth rates. Because no industry deflators were available GDP deflators have been used to adjust for inflation. Data for the following countries: Australia, Belgium, Canada, Czech Republic, Finland, France, Germany, Italia, Japan, Korea, Netherlands, Norway, Poland, Spain, Sweden, UK, USA

117. An often cited reason for the decline in R&D investments in industry is that with the introduction of competitive forces in the energy industries, firms (in particular electric and gas utilities) have diverted resources committed to longer term R&D to lower risk market-oriented projects[84]. Although this may be true, an even stronger decline applies to refining and the nuclear sector where the liberalization process has been less pronounced. This might coincide for a large part with the declining public R&D budgets for nuclear energy.

Energy R&D intensity

118. Another way to look at the development of energy R&D expenditures is to express them as a percentage of total turnovers (this is called the R&D intensity). This normalises R&D expenditure to make it comparable with R&D expenditures in other parts of the economy. In figure 9 the development of R&D intensity in the energy sector is compared with the R&D intensity of the manufacturing sector. The R&D intensity of the energy sector has been more than halved from an already low level to 0.33% whereas the R&D intensity of the total manufacturing sector has increased slightly to 2.65%.

Figure 9 R&D Intensity Energy Sector and Other Manufacturing Sectors



Source: OECD STAN Indicators Database 2005. R&D intensity = (industry R&D expenditure / industry production) * 100

V.3 Energy R&D in relation to government subsidies

119. We can also compare R&D expenditure with other subsidies and policies supporting the energy sector.

120. Estimates of support to energy consumption and production in the OECD area are either incomplete or very approximate.[85] The subsidies are not visible in national accounts and to the extent they are reported in budgets, they are often hidden behind vague programme descriptions. Moreover, in OECD countries, a very large proportion of subsidies to the energy sector are provided through tax concessions or government loan guarantees, support which does not normally appear in the published budgets but which directly affect costs or prices. No reliable data are available but some estimates and projections have been made by several institutes and researchers.

121. In 2001 the International Energy Agency estimated that subsidies to energy producers in OECD countries were running at around US$20-30 billion a year. For the greater part these subsidies benefit mature fossil fuel technologies. Other researchers have suggested the actual number may be closer to US$80 billion a year for the OECD countries.[86] Government spending on research and development is however included in the latter higher subsidies estimates. As we have seen, government expenditure on energy-related R&D hovers around $9 billion a year.

122. Energy subsidies in emerging and developing countries are relative abundant, although over the 1990s energy subsidies in the former centrally-planned economies of Eastern and Central Europe have been decreased rapidly. In its *World Energy Outlook 1999* the IEA estimated under-pricing of energy products in eight of the largest countries outside the OECD: China, India, Indonesia, Iran, Kazakhstan,

Russia, South Africa en Venezuela. On average, for all these countries end-use prices were found to be approximately 20% below their opportunity cost or market-based reference levels.

123. In 1997, the World Bank estimated annual fossil fuel subsidies at $48 billion in 20 of the largest countries outside the OECD and $10 billion within the OECD. A 2004 report from Eurelectric looked at direct support levels for renewable electricity supply in 2001 in 10 countries of the EU. It estimated subsidies (price support to producers, feed-in tariffs, etc.) to be € 3.3 billion in 2001.[87]

124. The *World Energy Assessment* (2004) reprinted a table from several studies from André de Moor and Cees de Beers in which they made an educated guess of energy subsidies totalling $244 billion per year (see table 9).

Table 9. Cost of Energy Subsidies, by Source, Based on Data Over 1995 – 1998 (US$/year)

	OECD Countries	Non-OECD Countries	Total
Coal	30	23	53
Oil	19	33	52
Gas	8	38	46
All fossil fuels	***57***	***94***	***151***
Electricity	-	48	48
Nuclear	16	Nil	16
Renewables and end-use	9	Nil	9
Non-payments and bailout	0	20	20
Total	***82***	***162***	***244***

Source: taken from WEA (update 2004) André de Moor, "Towards a Grand Deal on Subsidies and Climate Change", Natural Resources Forum 25, no. 2 (May 2001); Cees van Beers and André de Moor, Public Subsidies and Policies Failures; How Subsidies Distort the Natural Environment Equity and Trade and How to Reform them (2001).

125. Although these estimates of energy subsidies need to be treated with great care, it is clear that governments are subsidising the energy sector, often in ways that are both economically and environmentally harmful, and much more lavishly than they are prepared to fund R&D. Furthermore, subsidies to mature fossil fuel technologies still seem to outweigh the subsidies directed to achieving a higher deployment of renewable energy.

126. While these subsidy schemes may be supporting a wide range of policy objectives, the comparison does show clearly that a switch of resources away from subsidies to current consumption in favour of research in support of a secure and sustainable energy supply could be achieved within existing budgetary limits.

V.4 Adequacy of energy R&D priorities

127. Judging the adequacy of energy R&D priorities and expenditure is not an easy or straightforward task. The public benefits are uncertain and, if any, they only occur in the long term whereas the costs are very certain and competing in the short term with other political priorities. For all that, when the uncertainties are large, as in the case of global warming, it may be a sensible strategy to invest in options

that reduce the uncertainties. This could be the case even if the value of the option is uncertain. If they can be gained at relatively little cost while there is the possibility of a very high pay off, the expenditure may be well worthwhile.

128. Each country should set its own R&D priorities based on its particular resource endowment, technological expertise, industrial strengths and energy markets[88]. For this reason it is difficult to make a cost benefit analysis of energy R&D expenditure in general. What is possible is to place R&D priorities as revealed by current R&D expenditure alongside the long term potential of new energy technologies.

129. Table 10 summarises what we know about the technical and economic potential of a range of energy technologies. In addition to technical potential, an assessment is made of both the maturity of the technology and the remaining R&D challenges. A key question for policy makers is whether the overall portfolio of R&D investments stated in the last column represents a good balance.

Table 10 Summary of technical and economic potential

	Technical potential			R&D gap		Competitiveness Potential		Budget
	Resource availability	Energy security	Level of Carbon free supply	Technical maturity	R&D challenges for reaching full potential	Price on CO_2	No price on CO_2	Share of total public IEA R&D expenditure in 2004
Renewables								
Solar PV	+	+	+	+/-	––	+/–	–	4.0%
Solar thermal	+	+	+	+/-	0	0	+/-	0.9%
Solar heating / cooling	+	0	0	0	0/-	0	+/-	0.5%
Bioenergy	–	0/-	0/+	+/-	–	0/+	0	2.8%
Wind	0	0/+	0/+	+	+	+	0/+	1.3%
Geothermal	–	––	0/+	+	+	0/+	0/+	0.5%
Hydro	––	–	0/+	+	+	+	+	0.3%
Nuclear								
Fission	+	+	+	+/-	–	+	+	33.3%
Fusion	+	+	+	––	––	nb	nb	7.6%
Fossil fuels								
Generating Efficiency	+	+	0	+	+	+	0/+	~10%
Substitution techn.	+	+	–	+	+	0/+	+/-	
Capture and Storage	+	nb	+	+/-	0/+	+	––	1.1%
Hydrogen and fuel cells	nb	+	+/-	––	––	0/-	–	~12%

Legend: + = positive; 0 = not significant positive or negative; – = negative; –– = very negative; +/- = impacts vary from positive to negative depending on technology.

130. Without drawing any conclusions we make the following observations:

- Given the enormous scale of the resource, solar research is receiving modest funding (although its share has been rising in recent years). In particular the share of solar thermal seems to be relatively modest given its potential, notably in developing countries.

- The share of mature technologies such as wind, geothermal and hydro with limited further research potential seem to match rather well with their share of the portfolio.

- Although absolute levels of nuclear R&D have been declining in most countries its share in the total R&D portfolio is still overwhelming. This is primarily because of the high budgets for nuclear energy in Japan and France.

- The declining share of public funding for mature fossil fuel research and development priorities seems to be justified given the maturity of the technology and the strong incentives for the private sector to invest in them. These technologies are often commercially exploitable because they increase efficiency or make extraction and production processes more effective.

- Capture and Storage R&D has been increasing but is still *very* low with an estimated budget of roughly $100 million a year. The benefits of the technology are mainly societal and a larger government role seems therefore legitimate. There is still a shortage of sizeable R&D projects in order to advance technological understanding, increase efficiency and drive down costs. To achieve full scale production in a timescale that can significantly influence CO2 concentrations, the IEA states that at least 10 major power plants fitted with capture technology would need to be operating by 2015. Public investment in CCS technology would need to increase approximately fivefold to meet this target [89].

- Global energy supply projections indicate cumulative infrastructure investment of around $ 17 trillion up to 2030. That is $654 billion per year. If the additional capital cost of near-zero carbon technologies were of the order of 10% (they could well be higher), that would require an additional $60 billion per year. If there is no government imposed price on carbon, zero-emissions technologies will lack any commercial rationale. And it is highly unlikely that public subsidies would be available to cover the additional investment costs. Understanding these magnitudes is important because public R&D by itself is not a solution to mobilising resources on the scale required to deploy the technologies discussed about in this paper.

VI CONCLUSIONS

131. Two frequently raised concerns form the basis for this paper. The first is security of supply. This arises principally in respect of the concentration of remaining oil supplies in politically unstable regions of the world. How can the world's leading economies insulate themselves from the risk of disrupted energy supplies?

132. The second is sustainability given the need to stabilise atmospheric concentrations of greenhouse gases at levels that minimise the risks of significant climatic disruption. How can the global economy satisfy a strongly rising demand for energy services without a huge increase in total greenhouse gas emissions?

133. In respect of the first question, the paper concludes that security of supply is not a particularly significant problem in the medium to long term. While oil and (to a lesser extent) gas supplies are certainly concentrated in geo-politically sensitive regions, future demand for liquid and gaseous fossil fuels can be supplied from coal. Indeed, all fossil fuels are substitutable for one another and the technologies needed for those substitutions are available and (at current oil prices) economic.

134. The second question, satisfying future demand without a massive increase in emissions, is less easily disposed of. Despite efforts that now span more than 15 years, countries have found it extremely difficult to construct a regime that will limit emissions. On a business as usual basis that takes account of

current limitations commitments and the historical rate of technological change, emissions are still set to rise by more than 80% by 2030 over 1990s levels.

135. In assessing the prospects for new technologies, it is important to have a clear understanding of the strong competitive edge traditional fossil fuels have in the marketplace. Their abundance and affordability – and the sheer scale of the investments made in them over several generations – make an easy move away from them hard to envisage.

136. A much talked about option in this regard is biofuel. While biofuel will be a useful and cleaner addition to liquid fuel in those countries where it can be produced cheaply (such as Brazil), it is very unlikely to be able to replace fossil carbon fuel on account of its requirements for land. Even significant technological advances such as the conversion of cellulose to ethanol will not provide a complete solution given the significant uncertainties that surround just how much photosynthetic activity at the planetary level can be practically diverted to this purpose[90]. Hydrogen is still far from being competitive and will only be part of the solution beyond 2030 or latter.

137. The conclusion must be that while rising oil prices will certainly provide a spur for greater vehicle efficiency, the ability to convert resources such as coal and gas into liquid fuels competitively at well below today's peak oil prices means that the next generation of motor vehicles will not have radically different emissions.

138. More options apply with respect to new energy technologies for electricity generation but their economic competitiveness remains problematic. Regarding the technical potential for renewables it is important to keep in mind that it would only be possible – at least in theory – to meet future demand from renewable sources if there was widespread recourse to solar energy. This is the one renewable source that is superabundant although there are non-trivial issues relating to both transmission and storage. Wind, bio-energy and unconventional geothermal energy suffer from greater limitations. From an economic point of view, fossil fuel electricity plants, especially combined cycle gas turbine plants, will most likely remain the technology of choice because of their low overall cost. Given the size and distribution of coal resources a return to coal fired power plants is a real and strong possibility.

139. For these reasons it is hard to avoid the conclusion that in the absence of any decisive policy intervention the global economy will remain heavily dependent on fossil fuels. Their share could in fact increase if existing nuclear power plants are not being replaced with new ones and nuclear capacity is not expanded. The next generation of energy technologies will almost certainly be incrementally more efficient but the gains from that efficiency are almost certainly going to be swamped by the sheer increase in generation. It is interesting to reflect on the implications of projected demand. Primary global energy demand is presently around 15TW. That is forecast to double to around 30TW by 2050 (based on moderate assumptions for population growth and economic development). Currently, only about 3TW of the 15TW global demand is met from carbon-free supplies.

140. Stabilising CO_2 concentrations at twice the world's pre-industrial level in 2050 would imply supplying carbon-free energy in 2050 on a scale equivalent to the entire current supply of energy from fossil, nuclear and renewable primary resources. Given the cost and variability of many renewable energy sources, a likely on-going reliance on fossil fuels places particular urgency on proving the practicality of large scale carbon capture and storage.

141. Whether we are talking about new renewable forms of energy or clean fossil fuel, there are significant costs. If a negotiated limitation on emissions designed to created a 'market pull' incentive to bring these technologies on-stream is beyond realistic diplomatic possibilities, the question then arises whether 'technology push' policies can achieve the same thing. Research, development and deployment expenditures by governments are one such policy lever.

142. It is difficult to say what level of investment in R&D would be needed to bring new technologies forward. But the trends of what is now being spent are not encouraging. While public budgets for R&D have been on rising in recent decades, public expenditure on energy R&D has been declining. This decline has not been compensated by private sector expenditures which have also declined in absolute terms. If we measure R&D intensity (R&D expenditure as a percentage of total turnover) in the energy sector, the level has more than halved from an already low level as opposed to a trend of slightly rising R&D intensity in other sectors. It is not difficult to see that these trends have been in stark contrast to the climate change challenge that seems to have become more compelling over the same period.

143. This paper does not seek to draw any conclusions about where the weight of R&D expenditures should be concentrated or the absolute magnitude of resources that should be applied to energy-related R&D. What is clear is that much speedier action is needed and on a much bigger scale. As governments are not inclined to use market incentives to spur investments, reliance on public research, development and in particular deployment will need to be larger if any value is to be given to mitigating the impact of climate change. That said, it is unlikely that the sheer scale of investments needed could be financed through taxation and public budgets.

144. Clearly, R&D is not the only lever available to countries seeking to address cleaner and more secure supplies of energy. Neither are their technological ‘silver bullets’ available to solve energy-related problems. Improvements need to be made incrementally across a wide range of fronts including the efficiency with which energy is used in a wide range of applications and built environments, and the extent to which the true costs of energy used are priced in the marketplace. But R&D will be an important part of the policy mix.

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ANNEX 1

Decimal Prefixes

10^1	deca (da)
10^2	hecto (h)
10^3	kilo (k)
10^6	mega (M)
10^9	giga (G)
10^{12}	tera (T)
10^{15}	peta (P)
10^{18}	exa (E)

General Conversion Factors for Energy

TO:	TJ	GCAL	MTOE	MBTU	GWH
From:	Multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

ENDNOTES

[1] Smil (2003).

[2] WEA (2000), Chapter 9, *Energy Scenarios*, This moderate business-as-usual scenario was taken from an earlier publication Nakicenovic, et al (1998) which was also used for the scenario's in the IPCC (2001) report.

[3] *Financial Times*, Monday 16 January 2006.

[4] Increase in global temperature by 2100 relative to pre-industrial levels for different stabilisation levels (expressed as CO2 equivalent).

Stabilisation Level (CO2 equivalent)	*Temperature change – based on IPCC 2001 climate models*	*Temperature change – based on 2004 Hadley Centre ensembles*
400ppm	1.2 – 2.5 C°	1.6 – 2.8 C°
450ppm	1.3 – 2.7 C°	1.8 – 3.0 C°
550ppm	1.5 – 3.2 C°	2.2 – 3.6 C°

Source: HM Treasury; Stern Review: technical annex (www.sternreview.uk.org)

[5] IPCC (2001).

[6] See for example: http://dataservice.eea.eu.int/atlas/viewdata/viewpub.asp?id=1164.

[7] Hoffert (1998). The analysis is based on the 'business-as-usual' scenario of the second assessment report of the IPCC but its basic assumptions are still relevant today.

[8] This clustering of technologies is arbitrary. Other groupings are just as much possible.

[9] Herring (2005)

[10] Lackner and Sachs (2005) and Jaccard (2005)

[11] Solar radiation is radiant energy emitted by the sun, particularly electromagnetic energy. About half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum (IPCC 2001).

[12] The average energy of sunlight falling on a square meter of the Earth's surface – the solar radiation absorbed by surfaces – averages 168 W/m2. Smil (2003).

[13] The assumed annual clear sky irradiance depends on a region's latitude (geographic position). The minimum assumes horizontal collector planes (between 180 and 320 W/m2) and the maximum assumes two-axis tracking collector planes (between 420 and 480 W/m^2), the latter having a better angle to the sunlight. The assumed annual average sky clearance is around 44% as a minimum and around 90% as a maximum. The amount of unused land available per region is taken from the statistical database of FAO and represents 26% of the total land surface on earth. While this should be considered a rather large amount, to calculate the minimum and maximum only 1% respectively 10% of this unused land is taken into account. That means between 0.26% and 2.6% of the total land surface has been taken into account to calculate the theoretical potential of solar energy. The range between minimum and maximum is large (a 60-70 fold difference) because minima and maxima have been calculated for four variables.

[14] Photovoltaics (PV): 1) Wafer-based crystalline silicon (c-Si); 2) Thin films (www.eere.energy.gov/RE/solar_photovoltaics.html)

Concentrating Solar Power: 1) Parabolic trough systems; 2) Power Tower systems; 3) Parabolic Dish Systems (source: www.solarpaces.org).

[15] IEA (2006).

[16] Laboratory cell efficiencies are always higher because these cells do not require an optimization of cost/performance and because they cover only a small area. Laboratory efficiencies are now up to 25% for single-junction "one sun" cells and up to almost 40% for multi-junction concentrator cells. In the long term laboratory cell efficiencies of well beyond 50% can be envisaged, because the theoretical efficiency limit for photovoltaic conversion is over 80%.

[17] Smil (2003).

[18] Lenzen (1999).

[19] Whether traditional use of biomass for energy can be characterised as 'renewable' is a moot point given some of the pressures being placed on this resource by rising population and competition for land uses.

[20] IEA (2005c).

[21] WEA (2000).

[22] Smil (2003).

[23] The detailed study from Fischer and Heilig (1998) from which these numbers are taken assumes that only a fraction, overall in the order of 20% but varying with region, of the additional agricultural output needed will have to be met from expanding cultivated land. The other 80% will come from increased productivity (i.e. higher yields, reduced fallow periods and a larger number of crops per year).

[24] That is land that encompasses ecosystems classes 4, 8 and 9. The percentage of valuable forest and wetland from the total land potentially available for bioenergy feedstocks ranges from 26% in Middle East and North Africa to as high as 66% for the developed regions. Based on Fischer and Heilig (1998).

[25] WEA (2000) chapter 5.

[26] The WEA (2000) estimate is based on Johansson et al (1993).

[27] IEA (2006).

[28] Or 500 watts per square metre at 50 metres; WEA (2000) chapter 5.

[29] IEA (2005a)

[30] Cited in WEA (2000): Matthies, H.G., et al (1995), *Study of Offshore Wind Energy in the EC*, Verlag Natürliche Energien, Germany.

[31] IEA (2005a).

[32] Hoffert et al (2002).

[33] IEA (2006).

[34] WEA (2000) and Smil (2003).

[35] Cited in Smil (2003).

[36] on Citation from IEA (2006) in Stefansson, V. (1998), *Estimate of the World Geothermal Potential*, in Geothermal Training in Iceland: 20th Anniversary workshop, United Nations University, Iceland.

[37] Geothermal Education Office www.geothermal.marine.org.

[38] IEA (2006).

[39] Cited in WEA (2000) from World Atlas and Industry Guide.

[40] OECD/NEA (2002)

[41] WEA (2000), table 8.4 page 281.

[42] IPCC (2005).

[43] Lackner and Sachs (2005), Jaccard (2005).

[44] Presentation Lars Stromberg, OECD Global Science Forum Energy Conference 17/18 May 2006.

[45] The injected CO2 will return to the atmosphere in less than the ocean turnover time, which is less than 1000 years.

[46] Lackner and Sachs (2005).

[47] They are discussed in detail in IPCC (2005), WEA (2000) and IEA (2004). They can be grouped in 4 different systems (IPCC): 1) industrial processes; 2) post-combustion; 3) pre-combustion; 4) oxyfuel. Post combustion is a mature technology. Furthermore the application of pre-combustion capture is widely applied in fertilizer manufacturing and in hydrogen production. Finally oxyfuel combustion is in the demonstration phase.

[48] UNFCCC (2005), *Key GHG DATA, Greenhouse Gas Emissions Data for 1990 – 2003 submitted to the United Nations Framework Convention on Climate Change*.

[49] IEA (2005b).

[50] DOE, Energy Efficiency and Renewable Energy information Center, www.eere.energy.gov/RE/hydrogen_production.html . Technologies with the best potential for producing hydrogen to meet future energy demand fall into four general categories. (1) Thermochemical: a steam reforming process is used to produce hydrogen from such fuels as natural gas, coal, methanol, or even gasoline. To draw on renewable energy sources, the gasification of biomass can be used to generate a fuel gas that can be reformed into hydrogen. (2) Electrochemical: the electrolysis of water produces hydrogen by passing an electrical current through it. (3) Photoelectrochemical: produces hydrogen in one step, splitting water by illuminating a water-immersed semiconductor with sunlight. (4) Photobiological: generally use the natural photosynthetic activity of bacteria and green algae to produce hydrogen.

[51] A fuel cell works like a battery but differs from the latter in producing electricity from an external supply of fuel and oxygen as opposed to the limited internal energy storage capacity of a battery. It will produce electricity and heat as long as fuel (hydrogen) is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. Fuel cells can be used to power vehicles or to provide electricity and heat to buildings.

[52] In this sense, the IEA (2004) defines secure energy as being adequate, affordable and reliable.

[53] The scope of this paper doesn't allow for an economic approach that analyses the costs and benefits of governments' interventions to secure energy supplies. For an interesting analysis that concludes that intervention may often come at too high a price see CPB (2004).

[54] For a much broader analysis of different proxy measures of energy security see Blyth and Lefevre (2004).

[55] Ken Caldeira, presentation to the OECD Global Science Forum Energy Conference 17/18 May 2006: 1 Sleipner = 106 tCO2/year = 270,000 tC/year and abatement needed with 2% energy demand growth is approximately 12 PgC/year in 50 years. 2 Sleipners per day for the next 50 years = 10 PgC/year

[56] The economic potential is the technical potential plus its capital and operating costs compared with those of competing technologies and including the value of the product it delivers or the service it performs. IEA (1997).

[57] The technologies and plant types covered by the IEA/NEA (2005) study include units under construction or planned that could be commissioned between 2010 and 2015 and for which costs estimates through paper studies or competitive bids have been developed. For several reasons it is very difficult to compare the electricity generation cost of different technologies. Amongst others because of the difference that should be made between power plants that are supposed to provide base-load and plants that should provide peak-loads. The first may be more capital intensive than the latter because it is normally producing at a higher capacity and therefore fuel cost may be more critical than investment cost. As natural gas plants are more sensitive to fuel costs, while coal plants are generally more capital intensive the latter may be more suitable for providing base-load capacity whereas the first may be more suitable for peak-load. Furthermore fuel prices may differ between regions because of availability and transportation cost.

[58] According to Lackner (2005) the cost of Nuclear energy should come down by a factor of two. See also Jaccard (2005) Chapter 4.

[59] Sims, Rogner, Gregory (2003).

[60] In the State of the Union (31 January 2006) US President Bush has set a national goal of replacing more than 75% of US oil imports from the Middle East by 2025.

[61] Cornet (1999) and PCAST (1999).

[62] See for an interesting US perspective Chapter 1 of PCAST (1999).

[63] A more comprehensive attempt to capture the innovation process is done in the OECD Science and Technology and Industry Scoreboard that compiles a large group of indicators and is used to benchmark performance. The benchmarking exercise should only be used as a point of departure after which comparative policy analysis must be undertaken looking at the interrelation of these different elements and qualitative factors such as polices in other realms.

[64] See for example Guellec and Van Pottelsberghe de la Potterie (2001).

[65] Margolis and Kammen (2001).

[66] Sheehan and Wyckoff (2003) examine the factors that have contributed to the growing popularity of R&D intensity targets and analyse the economic and structural consequences of achieving the increased levels of R&D spending.

[67] OECD R&D database.

[68] The problem starts with the question how to define energy R&D. Most institutions use a definition that goes something like this: energy R&D is the linked process by which an energy supply, energy end use, or carbon management technology moves from its conception in theory (including necessary enabling basic research) to its feasibility testing and small scale deployment (Global Climate Change Group at the Pacific Northwest National Laboratory). Dooley (2000) presents a short overview of various data sources available for understanding investments levels in energy R&D and their strengths and weaknesses.

[69] The World Energy Council (2001) has conducted a major study on Research and Development statistics and provides almost a complete chapter on the methodologies used to collect R&D statistics and their pitfalls.

[70] http://www.iea.org/Textbase/stats/rd.asp

[71] IEA (2004b).

[72] IEA (2005b) and OECD (2006).

[73] Ministry for nuclear energy of the Russian Federation, *Strategy of developing atomic energy in Russia*. http://old.minatom.ru/presscenter/document/news/strat.pdf (Russian version), *National report of the Russian Federation on the Fulfilment of Commitments Resulting from the Convention of Nuclear Safety* http://www.minatom.ru/News/Main/view?id=15623 (English version)

[74] Malyshenko, S.P., and B.F.Reutov, *Russian R&D in Hydrogen Energy*, Ministry of education and Science of the Russian Federation and Federal Agency for Science and Innovations.

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[83] Utilities include investments in water R&D but it is unlikely that this will change the general picture.

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