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Key Tasks for future European Energy R&D

A first set of recommendations for research and
development by the Advisory Group on Energy

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Key Tasks for future European Energy R&D

A first set of recommendations
for research and development by the Advisory
Group on Energy

This position paper has been produced by the Strategic Working Group of the Advisory Group for Energy.

This paper is entirely the responsibility of the Working Group Members and is not represented as reflecting the views of the European Commission or of any national Government.

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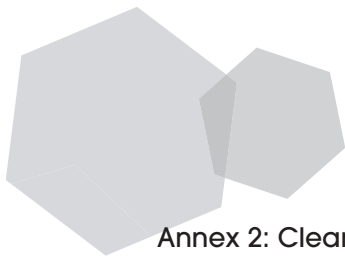
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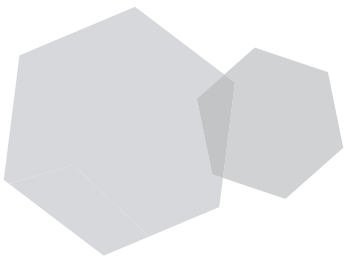
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PREFACE

In October 2002, the Commission asked its Advisory Group on Energy (AGE) to develop a strategic vision for energy R&D on a European scale, with emphasis on overcoming the usual compartmentalisation into different energy options and the barriers between the advocates of each option.

The objective was to support decision-makers with wide and thorough analyses of the issues at stake, and of the potential of various technology options to provide Europe with a sustainable energy supply and use.

The AGE embarked on a two-pronged approach by establishing two working groups:

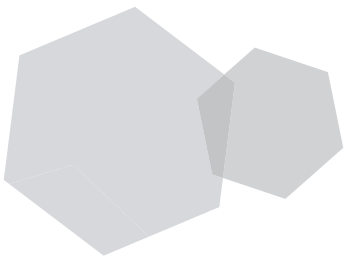
- A Strategic Working Group (SWOG) devoted to providing guidance to shape energy research strategies and agendas, at EU and Member State levels.
- A European Energy Research Area Working Group (ERAWOG) focused on the analysis and assessment of the potential for more collaboration and co-operation in various areas of energy research, together with practical recommendations to make ERA a reality in the energy field.

The analysis and recommendations put forward in this first report come from SWOG, but have been endorsed by AGE. They are important as the collective conclusions of many independent experts from very different backgrounds and specialisations, but they do not, of course, commit the European Commission. The SWOG members and others who are responsible for the thinking behind and the content of this report are Angelo Airaghi, Roger Ballay, Niels Busch, William d'Haeseleer, Wolfgang Dönitz, Cesar Dopazo, Gerhard Faninger, Alain Gerard, Patrick Ledermann, Peter Lund (AGE Chair), Frantizek Pazdera, Carlos Pimenta, Derek Pooley (SWOG Rapporteur), Erich Tenckhoff, Iacovos Vasalos and Alfred Voss (SWOG Chair).

Other members of AGE, of DG RTD and outside experts also contributed by making presentations to SWOG or by providing information and useful comment. They were Murray Cameron, Gerd Eisenbeiss, Jurgen Garche, Heather Greer, Sue Ion, Peter Hjuler-Jensen, Kaija Kainurinne, E. Kakaras, Frederick Marien (AGE and SWOG Secretary), Jerome Pamela, Odissefs Panopoulos, Michel Poireau, Josef Spitzer and Margot Weijnen. The group was assisted by Commission services which provided support to its work.

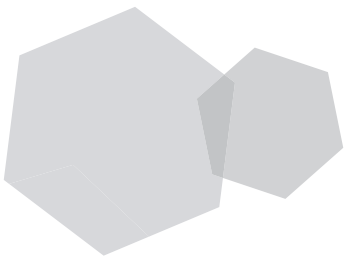
In this first report, SWOG has carefully analysed eight different promising technology areas. It has identified key research tasks in these areas where it concludes efforts should be focused. The technology areas examined in this report are: biomass, cleaner use of coal, fuel cells, hydrogen, nuclear fission, nuclear fusion, solar photovoltaics, and wind energy. Other potentially important issues and energy technologies will be examined in 2005, such as other renewable technologies, energy storage and transport, distributed electricity generation, system integration, energy efficiency and cross-cutting issues.

However, AGE has decided to release this present report now in order to contribute in a timely fashion to the important process of reflection presently under way to make energy research more responsive and more efficient in Europe.



MESSAGES FOR POLICY-MAKERS

1. Energy is vital! Like clean water and air, energy is essential to 'life' in the sense that it is a prerequisite for maintaining our standard of living. SWOG has unanimously concluded that a failure to make our energy use and supply much more sustainable – a failure which is likely unless we act urgently – is the biggest threat facing our developed economies.
2. Sustainable energy provision requires that energy supply is secure, affordable and clean (so that blackouts are prevented, rocketing prices are avoided, demand does not outpace supply, environmental impact is mitigated – both for local pollution and global climate change). Even international peace may be at risk because of the concentration of energy sources in highly sensitive geopolitical regions. Because of the difficulties and uncertainties involved in meeting these challenges and because of the long lead times for introducing new energy technologies, we cannot afford to waste time. We should start immediately and with real determination to achieve sustainable energy provision.
3. Although other instruments (such as taxes, subsidies or regulations) may be helpful, by accelerating market diffusion of recently developed energy technologies, SWOG believes that the only route to a sustainable energy system is through new or improved energy technologies that will have to be found through research and development. SWOG also thinks that the energy sector is the only community-level research priority facing such crucial challenges, which must be solved if economic, social and environmental decline is to be avoided.
4. To address the energy-related challenges appropriately, SWOG affirms that it is necessary to develop a portfolio of energy technologies and options. There is no certain solution: no single technology that can provide 'the' answer, nor is energy conservation (although very commendable and to be strongly encouraged) sufficient on its own. SWOG therefore believes that targeted research should be performed in a range of energy technology areas, but on well-selected topics, tackling key tasks where a technical breakthrough would dramatically improve our chances of making our energy system sustainable.
5. In this initial report, SWOG has identified a number of these key tasks. Most are not easy problems to solve and many will require strong, focused, Europe-wide R&D effort, i.e. R&D 'Schwerpunkte', directed to solving them. Enhanced support for cross-cutting issues and basic science research of relevance to energy could also help to achieve the required breakthroughs.
6. SWOG therefore regrets that Commission-funded energy R&D expenditure has decreased dramatically over time, in real terms by almost a factor of four over the past 25 years. Parallel declines have occurred in funding by EU Member States and by private industry, the latter accelerated during the last decade in the energy utilities by the liberalisation of the energy market.
7. It is SWOG's firm conviction that it is now reckless to maintain such a low level of energy R&D funding. It believes that the level should be restored in real terms to the levels of 25 years ago – that is, increased by at least a factor of four. Moreover, the new energy technologies which are needed will not be delivered quickly. The increased R&D effort should start now, and will have to continue over a long period of time.
8. SWOG firmly believes that, if nothing is done to increase and focus the energy R&D effort, our society will not meet the crucial energy challenges we face, with potentially dire consequences.



I. THE CHALLENGES AHEAD

The fuel shortages that plagued Europe in the aftermath of World War II have long been consigned to history. Even the energy crises which shook the Western world in 1973 and 1979 are now distant memories, their damaging economic impact largely forgotten. Nearly two decades of cheap, readily-available oil and gas have lulled the great industrial economies of Europe, the USA and Japan into complacency about energy, with ordinary consumers taking it for granted that the shortages and very high prices of the 1940s and 1970s have gone for good. Recent increases in the price of oil may have rocked that complacency although, we believe, only very slightly.

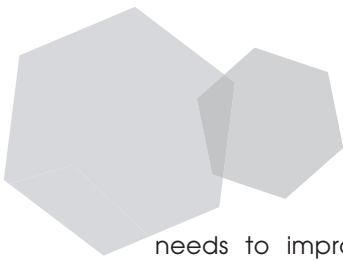
Yet many energy analysts believe that increasing energy demand is once again on a collision course with both supply constraints and unacceptable environmental impact. And this time, the problems seem certain to be truly global in scale and technically more difficult to overcome than in the past. There is a growing awareness that much of world's energy is produced and consumed in ways that cannot be sustained with current energy technologies if demand grows substantially, as expected, and/or environmental impact must be contained or reduced. The result will either be high energy costs or the need for restrictions/taxes on energy use, or both. Either will damage Europe's economy and make its industries relatively less competitive against countries which are technically better prepared to meet the energy challenges – and against those with cheaper labour and less energy-intensive manufacturing. On the other hand, the demand for new technology which can tap into new energy sources and use energy more efficiently will offer European industry major opportunities.

Trends in demand and supply

The forces driving increases in energy demand are no longer primarily in the developed world. Both China and India, each with populations bigger than Europe, the USA and Japan combined, have abandoned their policies of economic isolation and strict central control to espouse the free trade and market economics which made OECD countries so wealthy over the second half of the 20th century. Their economies are now growing rapidly, bringing wealth and a better life to their people but also an increasing demand for high-grade energy. They are no longer content to burn only locally produced firewood or even indigenous coal, although the latter will probably dominate their energy supplies into the medium-term future. Their demand for the oil and gas which currently fuels all advanced industrial economies is also growing spectacularly; in 2003, China's use of oil and gas grew by 38%!

Though individually smaller, many other Asian and Latin American economies are following the same path. Parts of Eastern Europe have now joined the EU! The result is that a further three-fifths of the world's population are heading for levels of economic activity and energy use previously enjoyed by only the privileged one-fifth, of which we are a part.

This potentially several-fold growth in global energy demand would perhaps have been less threatening if the rich countries of Europe, the USA and Japan had managed, over the last few decades, to find ways to reduce their own high energy demand by improved efficiency in energy use. They could then have passed on ways in which the fast-developing economies could become wealthy without as much energy use as in the past. The developing world certainly



needs to improve its energy efficiency and the developed world has certainly made commendable efforts in this respect, with the energy consumed per unit of wealth created in advanced countries reducing steadily, by about 1% per year over the last 50 years. But, during almost all of those years, economic growth in the developed countries has exceeded 1%, so that energy demand in OECD countries has almost always grown year-on-year, and there is no sign that this trend will change in the near future. It has become apparent that the large reductions in overall energy use in rich countries, predicted by some optimistic analysts in the energy-crisis years of the 1970s, have just not occurred. Nor will they do so in the future unless dramatic steps are taken, such as much heavier taxation on energy use. There are many worthwhile improvements in energy efficiency to be made but no technological miracles waiting to happen!

Others active in the energy industries during the 1970s crises predicted that so-called alternative energy sources, the 'new renewables' and nuclear fission and fusion, would provide abundant new energy supplies, economic, sustainable and independent of limited oil and gas reserves in politically sensitive parts of the world. Thirty years on, they still have not done so. Renewables contribute some 6% of EU primary energy, but this includes the traditional contributions from large-scale hydroelectricity and biomass (mostly wood and waste) combustion. Few new renewables are economic without subsidies and, as yet they contribute only 1%, although their contribution is now growing rapidly. Nuclear fusion remains only a distant possibility and fission is currently stalled, struggling to recover public confidence and, until recently, not economically competitive against gas. Fission's contribution to EU energy supply (15%) is very significant but is falling because of its general unpopularity following the Chernobyl accident and the low price of gas from 1986 until the large increases of recent years (since 2000).

As a consequence, the International Energy Agency predicts that the world will remain highly dependent on fossil fuels for the foreseeable future despite growth in energy demand – unless there are dramatic changes in energy policies. Yet many non-OPEC reserves of oil and gas, which were found and developed as a consequence of the energy crises of the 1970s, are now significantly depleted. For example, the UK sector of the North Sea has passed its production peak and is in decline. Many analysts believe that the situation in the North Sea is symptomatic of oil and gas production worldwide; we are at or near the peak in production and will simply not be able to meet greatly increased demand for fossil oil and gas. SWOG does not have the expertise to predict when global oil production will peak and consequently it is becoming impossible to meet future demand at anything close to current prices. Indeed, those with more appropriate expertise cannot agree whether that point of real and permanent oil price increase will be in ten or 50 years. But it is coming; the current situation is not sustainable!

Environmental Impact

Similarly, the concerns for the environmental impacts of energy use in the 1970s and 1980s were centred on the local or regional issues of acid rain from power stations and photochemical 'smog', caused by organic combustion residues from automobiles. Acid rain was reduced fairly easily by a combination of switching to higher-grade, low-sulphur fuels, flue-gas desulphurisation and better burners, and vehicle-exhaust pollution was reduced by making catalytic after-burners compulsory.

In contrast, today's environmental concerns focus on the global impact of greenhouse gas emissions, particularly the CO₂ produced when fossil fuels are burned. The evidence that CO₂ and other greenhouse gases are having a significant effect on the earth's climate has steadily become more convincing, with a number of climate simulation models converging on a global warming by 2100 in the range of 2-5°C. Though not all the impacts of climate change are necessarily bad, most seem likely to be unwelcome, with more frequent severe storms and floods, islands submerged permanently, tropical diseases moving further into temperate regions, hot dry summers in places not well-equipped to cope with them, etc.

What is certain is that a massive increase in the use of fossil fuels, accompanying economic growth in China, India and elsewhere, will greatly exacerbate climate change and may prove environmentally unsustainable. Consequently, almost everyone in the energy business accepts the urgent need to develop and deploy both traditional and novel 'carbon-free' energy sources – and ways of powering vehicles other than by fossil-fuelled internal combustion engines.

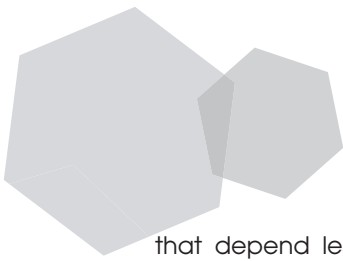
Large reductions in CO₂ (carbon dioxide) emissions from fairly conventional fossil-fuelled power stations may be possible by CO₂ separation and sequestration, although the economics of separation and long-term integrity of the CO₂ storage has yet to be determined. In contrast, although modern diesel engines do allow a useful reduction of CO₂ emissions from vehicles, and hybrid electric/internal-combustion-engine-driven vehicles can go even further, neither reduces CO₂ by a large factor. Very large reductions in CO₂ emissions from transport vehicles, comparable with the impact of CO₂ separation and sequestration on electricity generation, looks impossible without a switch to electric or hydrogen-fuelled cars, whose current performance and costs are far worse than conventional vehicle power plant. However, a carefully managed bio-liquid fuel system for transport vehicles could potentially eliminate net CO₂ emissions, with new biomass growth capturing the CO₂ in the engine exhausts.

Economic threats and opportunities

Difficulties in meeting the rising demand for energy with traditional fossil fuel supplies will inevitably cause energy prices to rise and have an adverse impact on European industries. The impact may be direct, with energy-intensive manufacturing finding its costs increased; or indirect, as consumer spending that has to be transferred to energy is no longer available for other consumption, and taxes previously levied on energy must be moved elsewhere. The initial impact on energy-poor regions such as the EU will be proportionally greater, as more of their wealth must be spent outside the EU on energy supplies, and could easily trigger an economic recession as it did in the 1970s.

The EU will also face a difficult challenge in making the contribution it would like to reducing global emissions of greenhouse gases. If the newly developing economies of China, India etc., and perhaps even the USA, are unwilling to place too many restrictions or taxes on the use of traditional fossil fuels by their industries, and the EU tries to do so without new, reasonably competitive, more-carbon-free energy technologies, then EU industries will find competing in the global market place more difficult than in the past.

But for every problem there is always an opportunity. No country will be immune from the difficulties in energy and all will be searching anxiously for new, competitive energy technologies



that depend less on oil and gas and can reduce CO₂ emissions. Those companies able to develop substitutes for traditional energy sources and methods of use will find an enormous market for their products across the world.

SWOG therefore believes that the EU has three powerful reasons for trying to solve the difficult energy problems we have outlined:

- to maintain the standard of living of EU citizens and the competitiveness of important energy-intensive industries;
- to put the EU in a position to take a lead in tackling the problems of global warming without harming its competitiveness and hence, as far as possible, protect its citizens from any adverse impacts global warming may have;
- to grasp the commercial opportunities to supply the emerging global needs for new, carbon-light energy sources, not dependent on oil and gas.

II. SWOG'S VISION OF A SUSTAINABLE ENERGY FUTURE

Doing nothing is certainly not a serious option, since modern life cannot continue without energy; it is essential for food, clothing and housing, through communication and transport to leisure and cultural activities. An adequate supply of economic energy is also a prerequisite for economic development and a decisive factor in environmental care. The EU Treaty on 'sustainable development, global change and ecosystems' makes sustainable development a central objective of the European Union and recognises that it can only be achieved if energy provision is also made sustainable.

However, SWOG believes that 'simple' sustainability in energy, in which the energy resources passed on by each generation to the next are not significantly different from those they inherited, can no longer be achieved by this generation. It is inevitable that our present high and growing reliance on oil and gas will significantly deplete the earth's fossil fuel resources before we can lessen our dependence on them. Nor is it now possible to ensure the environment remains essentially unchanged by energy use during our lifetimes. Further increases in atmospheric CO₂ are inevitable and some global warming will probably occur – indeed, it may already be occurring. Realistically, our societies cannot prevent it and they will have to cope with its consequences.

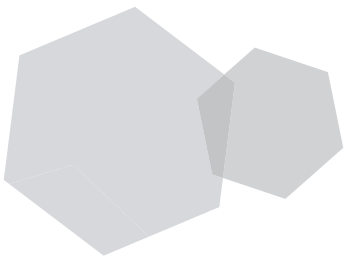
Broad sustainability

But sustainability need not be simple! The World Commission on Environment and Development (the Brundtland Commission), reporting in 1987, defined sustainable development as 'development that meets the needs of the present without compromising the ability of the future generations to meet their own needs'. Of course, it must provide equal opportunities and good social welfare within and across countries (and not just for the favoured few) and across generations (not just for a favoured period of time), as well as ensuring the conservation of the environment. But it can also incorporate economic and technological development and we should recognise that the path to a more sustainable energy future will never be static. It must be continuously redefined and rebalanced, not only to face new problems but also to incorporate new scientific knowledge and improved technological options which can make energy systems more efficient, affordable, accessible and environmentally friendly.

Thus, although our generation cannot achieve simple sustainability, it can develop new energy technologies and bring them into use, ready for our successors to use more extensively if they need them. It is in this way, rather than by simply conserving the oil and gas resources available to us, that we can ensure that the energy available to our descendants is functionally similar to that available to us – capable of providing energy for homes, industry and transport in different ways but at costs which will allow our descendants to enjoy wealth and comfort broadly similar to ours.

Similarly, the only environmental sustainability that is practical is to bring on-stream energy technologies which can initially lessen the growth in atmospheric CO₂, and eventually reduce it to acceptable levels, as well as ensure that other environmental resources are not significantly degraded.

SWOG believes that this 'broad' sustainability is consistent with the Brundtland definition and the only one that is practical in the present circumstances. It should be our target.



III. ACHIEVING BROAD SUSTAINABILITY THROUGH R&D

Achieving broad sustainability in energy is no soft option. In general terms, it requires that we:

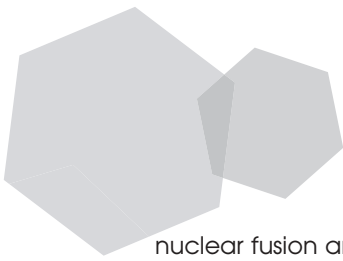
- ensure secure and reliable supplies of energy for the future;
- ensure that energy services are provided with a minimum use of scarce resources, i.e. at minimum total costs (both internal and external);
- ensure that the quantity of economically accessible energy handed over to the next generation is no less than we inherited;
- limit the use of slowly renewable energy resources, such as biofuels, to rates which do not exceed their regeneration rate;
- limit energy-related pollution and waste flows into the environment so that the absorption capacity of the natural environment is not exceeded;
- limit hazards and risks to human health from energy use so that they are below natural hazards and risks and those avoided by the use of energy.

Our current specific circumstances require the development and widespread deployment of energy technologies which do not depend on oil and gas and do not release significant quantities of CO₂ into the atmosphere. This implies significant changes in the energy industry which cannot be made quickly; with a turnover of roughly €3,000 billion world-wide, it inevitably has substantial inertia. Maximum effort to bring about the required changes must therefore be applied as soon as possible.

Fortunately, there are many technical options for the new energy technologies required, some with exciting potential. Unfortunately, none is without disadvantages that have so far prevented their widespread use and will have to be overcome. To achieve even broad sustainability, we will therefore have to:

- demonstrate the practicality and costs of new technologies;
- improve the performance and/or reduce the costs of existing technologies;
- increase equipment availabilities and lifetimes to make all the potential solutions more attractive and easier to use;
- ensure that new energy technologies achieve high levels of safety and have low impacts on human health and the local and global environment.

This task of developing and improving energy (or any other) technologies is the role of research, development and demonstration (all three are covered by the Frascati definition of R&D). Thus, *short- and medium-term* R&D funds will be needed to improve existing non-oil-and-gas, non-CO₂-producing energy technologies to the stage where their economic competitiveness and overall acceptability is sufficiently good that they become preferred options for new energy investment, without government intervention. *Medium- and longer-term* R&D funds are necessary to attempt the development of new energy sources and carriers such as bio-liquids from ligno-cellulose,



nuclear fusion and hydrogen which, if they become practical and reasonably affordable, would be very clean and sustainable.

SWOG was tasked to define a strategy for EU energy R&D which can move Europe towards a 'broadly sustainable' energy system. It chose to begin by identifying what it believes are the most important R&D tasks within that programme. Although it was in no way constrained by earlier work, it does recognise that its predecessor, the EU 'Energy Research Working Group' (EWOG) took an important first step here. That group looked at the possible technical contributors to a non-oil-and-gas, non-CO₂-producing energy system, namely:

- Improved energy efficiency
- Renewable energy sources
- Cleaner use of coal and other fossil fuels
- Nuclear fission and fusion energy
- Hydrogen as an energy carrier

Having considered these in a very broad-brush way, it concluded (EUR 19790; January 2001) that, "... given the present status of these technologies and the uncertain future, none can be relied on for more than a contribution to solving the overall problem and all options should be kept open and further development be pursued...". Having considered the matter again, SWOG agrees with this conclusion that none of these broad options on offer is so certain to succeed that others can safely be abandoned, nor is any one without sufficient promise that it should be ignored entirely. Key R&D tasks will be found across a very broad front of technologies.

Funding for EU energy R&D

SWOG does recognise that following up every technological possibility is not a realistic option. It would be extremely expensive and even a very large economy such as the EU may be unable or unwilling to do so. But focusing limited resources on one or two favoured technologies is not sensible either since the outcomes are still too uncertain.

SWOG therefore deplores the relentless erosion of energy R&D expenditure over the last 25 years. This has led to a level of funding which is neither commensurate with the importance and severity of the energy challenge nor with the conclusion that a wide range of technologies must be pursued to be sure that the challenge can be met.

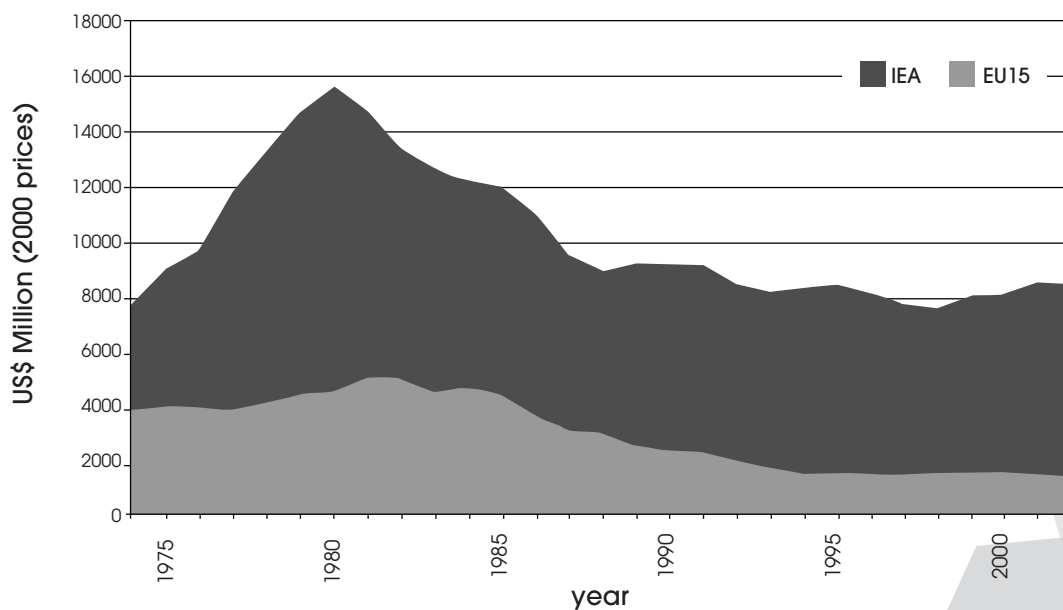
For example, European Commission expenditure on energy R&D is illustrated in the table below:

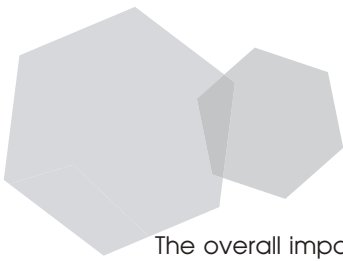
Framework Programme number	Total R&D (G€)	Energy R&D (G€)	Energy R&D (% of total R&D)
Before Framework Programmes			66
1 - 1983 to 1986	3.8	2.508	66
2 - 1987 to 1990	5.4	2.700	50
3 - 1991 to 1994	6.6	1.506	23
4 - 1995 to 1998	13.2	2.904	22
5 - 1999 to 2002	14.9	2.700	18
6 - 2003 to 2006	17.5	2.040	11.6

In face-value terms, expenditure is now less than it was 25 years ago, in real-value terms it is very much less and, as a percentage of the total Community R&D, it is roughly six times smaller than 25 years ago.

These reductions in EU Commission funding for energy R&D reflect government funding more generally, as shown in the diagram below which uses data provided by all those national governments which are members of the International Energy Agency. Note that the reduction factor has been greater in EU countries than for other members of the IEA.

Government energy R&D Expenditures 1974 - 2002





The overall impact of these cutbacks has been exacerbated by the substantial de-regulation of the energy industries in Europe that has occurred over the past ten to 15 years. The now private-sector energy companies have to balance the use of funds for R&D against dividends and capital investments to increase shareholder value (to protect the company against hostile takeover), and against price reductions for customers (to protect the company against competing suppliers). Energy companies no longer have an obligation to ensure supplies in the long-term future although they will, of course, take steps to ensure their business continues for as long as it is profitable. Consequently, they no longer take such a long-term view as they did when they were public sector monopolies, and they now fund less R&D.

SWOG therefore believes that the European Commission and EU Member States should increase the public sector resources available for energy R&D, at least to the same level in real terms as 25 years ago, when energy supply and use was last seen as the key issue it has once again become. SWOG believes that, for the enlarged European Union (EU-25) the present level of EC energy R&D expenditure should be increased by at least a factor of four.

The EU energy industries receive significant public subsidies: 29.2 billion euros in 2001, according to the European Environment Agency (see table below), which dwarf the energy R&D expenditure. This support is provided as a mixture of direct subsidies, financial incentives, feed-in-tariffs, and tax reductions, and the figures include public sector R&D expenditure. However, much of this support is technologically backward-looking, such as the support for deep-mined coal, for the oil and gas from which we need to turn, and for the decommissioning of old nuclear facilities. With the exception of the support for renewables, it is unlikely to contribute much to future energy problems.

Energy Source	EU 15 Subsidy in 2001: G€
Coal	13.0
Oil and Gas	8.7
Nuclear Fission	2.2
Renewables	5.3
TOTAL	29.2

SWOG believes that there needs to be a better balance between funding to solve past problems, to meet short-term energy needs, and to position ourselves for a more sustainable future.

IV. MAKING EFFICIENT USE OF ENERGY RTD RESOURCES

Having deplored the erosion of funds for energy R&D, SWOG does accept that there will never be enough money to do everything which might help us to meet the energy challenges ahead. A strategy for EU-wide energy R&D must try very hard to identify the really key tasks and eliminate work which is either:

- unnecessary, because the desired developments will happen anyway, without the involvement of the Commission or governments; or
- unproductive, because the technical or economic challenges are too severe and therefore the R&D is unlikely to succeed; or
- insignificant, in the sense that the technology, even if successfully developed, cannot be applied widely and its contribution to energy supplies will therefore be small and/or local.

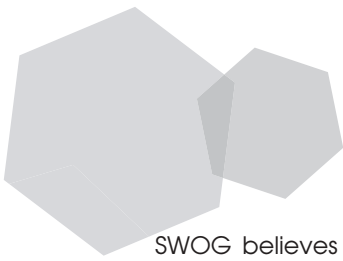
SWOG believes the best energy R&D strategy is to focus resources where concentrated and effective R&D is likely to have a big impact on the problem we face – i.e. in a few R&D ‘Schwerpunkte’.

Therefore, the main thrust of the first phase of SWOG’s work has been to look at prima facie important technology options which lie within the broad groups considered by EWOG, and to evaluate them in order to try and identify key R&D tasks which have the greatest potential to change the EU energy scene and which seem likely to realise that potential given well-directed R&D effort, but which are unlikely to be developed without EU-wide involvement.

The last point is crucial for the Commission’s Framework Programme. There ought to be clear added value in having an EU-wide programme as opposed to separate programmes in individual Member States. This added value may come either from allowing Member States to carry out programmes otherwise beyond their means (e.g. fusion), or in enabling common standards to be developed which are crucial for the deployment of the technology (e.g. CO₂ sequestration), or in deploying a wider range of talents and skills to tackle technically novel and perhaps intractable problems (e.g. biological routes to bio-liquids). It is also important for the Commission to guide R&D funds to where Europe is likely to sustain globally competitive industries, with the consequent benefits for employment and the balance of payments. In order to allow EU funds to be focused in areas where there is clear European added value, an important part of the SWOG exercise was to set aside any EU-wide concern for that R&D which can either be done equally well in Member States or is without sufficient promise. But the main work has been to identify those R&D tasks which are important for the success of each promising new energy technology.

The choice of technologies

In looking at some technologies and not others, SWOG recognises that it may be misunderstood. Almost all energy technologies have their enthusiastic supporters who believe that their particular ideas are important for the future, and it is therefore important to explain the process by which its key R&D tasks were identified. Not everything can be key because, although it seems likely that no single technology can meet future needs, it is equally likely that not all will be needed.



SWOG believes that spreading scarce R&D resources across too broad a front is not the best strategy – even its initial choice of technologies was more selective than EWOG’s broad conclusions (paragraph 26) in two important ways.

First, it has not yet considered improved energy efficiency. As EWOG said in its report, improved efficiency at the point of use relies on “a mosaic of more-energy-efficient products and processes that are continually being invented, adopted, improved and eventually discarded for something better”. Few of the individual technologies in the mosaic have a high potential on their own, although collectively they are very important. Moreover, most developments here will occur without the help of EU-wide R&D, as manufacturers develop better products to improve their competitive edge and users buy more efficient equipment for better performance or to save fuel costs. Also, improving the energy efficiency of industrial processes (such as paper-making or materials fabrication) or of particular industrial, commercial or domestic equipment usually requires industry-specific knowledge and insight beyond the general competence of SWOG.

SWOG has therefore not evaluated improved-energy-efficiency options so far, with one important exception – that is fuel cells which are likely to be deployed primarily near the end use for the electricity they make from chemical fuels. They have the potential to make a substantial impact on the efficiency of electricity generation from fossil fuels and, more importantly, could revolutionise surface transport by allowing vehicles to be driven by hydrogen fuel, essentially pollution free and at high-energy efficiency. Therefore, SWOG explicitly included fuel cells in its phase-1 programme.

Neither did the group consider explicitly two other important aspects of energy efficiency, namely the conversion of fossil fuels to electricity via gas and steam turbines and their conversion to motive power for vehicles via internal combustion engines. However, some generic issues here are dealt with in our report on the ‘cleaner use of coal’. It is probably worth emphasising at this point that SWOG uses ‘coal’ as shorthand for the various non-oil-and-gas fossil fuels such as heavy oils, tar sands and coals. These are more widespread and cheaper and could certainly reduce our reliance on oil and gas, but they are generally dirtier and emit more CO₂ per unit of useful energy.

The second difference between our choice of technologies and those in paragraph 26 is in our treatment of renewables. Renewable energy technologies are a large and diverse group, albeit with less diversity than end-use technologies. SWOG has therefore chosen three of the ‘new renewable’ technologies for the first phase of its work, the three which, *prima facie*, have the best potential for growth, namely biomass fuels, wind power and solar photovoltaics. SWOG recognises that a fourth renewable, traditional large-scale hydropower is an important electricity generator, but its potential for future growth in the EU is limited and the constraints on that growth are not primarily technological. SWOG also recognises that other renewables, such as geothermal and ocean energy, might make useful contributions to Europe’s energy.

Biomass fuels and wind power are already important and generally recognised as having high potential for the future. Thus, the IEA ‘World Energy Outlook 2004’ projects that non-hydro renewable electricity generation in OECD Europe in 2030 will supply about 16% of our electricity, consisting of 5.1% from the combustion of biomass (and waste) and 7.8% from wind power. The European Commission, in its ‘European Energy and Transport – Trends to 2030’

makes different predictions for the EU-25, giving wind power an 11% share of electricity generation in 2020, and biomass and waste about 4%. Their numbers differ but both agree that biomass and wind are likely to make the largest contributions, supporting SWOG's choice of biomass and wind power.

There is less agreement about the future importance of solar photovoltaics (PVs). PVs are currently much too expensive for commodity energy supply, but if they became sufficiently cost competitive, their potential would be very large. We could then expect their wide use in southern Europe with wind power more important in northern Europe. SWOG therefore decided to include solar photovoltaics in its initial programme.

The technologies SWOG has considered so far, listed in alphabetical order, are therefore as follows:

- Biomass (including agricultural, industrial and municipal waste)
- Cleaner use of Coal
- Fuel Cells
- Hydrogen as an Energy Carrier
- Nuclear Fission
- Nuclear Fusion
- Solar Photovoltaics
- Wind Energy

SWOG believes it is in these eight technologies that most of the important critical issues or turning points in our future energy system can be found. Here, a few successful R&D 'Schwerpunkte' could make big changes to the way energy is provided and used in the future. But, in choosing these eight, SWOG recognises that other technologies cannot be ignored, energy storage and better grid management, for example, and it will turn to them later.

Analysis of the technologies and identification of key R&D tasks

Most SWOG members had some familiarity with all eight of the chosen technologies but the group tried to ensure every member gained a good appreciation of all by arranging two presentations on each, one by the SWOG member most familiar with the field and a second by an outside expert. The speakers were given a specification for their presentation which ensured they covered the key issues, and SWOG was able to question and discuss them extensively. The SWOG rapporteur then set down in a 'synthetic report' what appeared to be the Group's appreciation of and conclusions about the technology in a standard format for subsequent discussion, modification and eventual approval by SWOG. These synthetic reports on individual technologies comprise the annexes to this report.

In each case, SWOG assessed the technology against a common set of criteria, in part to test and either confirm or change its judgment about the likely importance of the technology and hence the priority it should be afforded in R&D funding, but also to identify where the weaknesses are



which R&D must diminish or remove, and hence to identify the key R&D tasks that are likely to have a decisive impact. The criteria were:

Potential Economic Contribution within the European Union. How much electricity, gas, liquid fuel or coal in total is likely to be saved or made available economically (without subsidies or carbon taxes) in the EU by using the technology in a market where energy prices are at:

- current levels (assumed in this study to be around \$30 per barrel) and assuming current or confidently expected costs for the technology;
- two times current levels (or technology costs that are half current costs);
- four times current levels (or technology costs four times less than current costs).

Many new technologies are uncompetitive at current energy prices and the economic contribution at current levels is therefore often zero. A technology may become competitive either because the costs per unit of output are reduced or because competing energy prices rise. These prices (of continuing to use conventional energy sources) could rise either because of supply/demand imbalance at current price levels or because CO₂ emissions are penalised. We have folded these three price/cost factors together. Once technologies are competitive, their contribution may or may not be limited by other factors. Tidal electricity, for example, would be severely limited by the relatively few good sites available, and waste combustion by the amount of waste generated.

Health and Safety Impacts. What is the complete life-cycle impact on human health and safety, via routine operation and accidents, per unit of delivered energy?

- to the workforce – where risks are usually higher but also more acceptable;
- to the general public nearby, in the EU and worldwide.

Environment Friendliness. What is the complete life-cycle impact on the local and global environment per unit of delivered energy?

- locally in terms of emissions, land use, visual intrusion, waste disposal;
- globally in terms of CO₂ or other greenhouse gases.

Input Sustainability. How readily available, over a long period of time (many decades), are the input fuels and other materials required, not necessarily within the EU but globally?

Security of Supply. Are the sources of the fuels and other materials required and the operation of the equipment secure, or is there a dangerous dependence on imports from politically difficult geographical areas, sensitivity to cartels, to terrorist attack, etc.?

Compatibility with EU needs. Can the energy be produced roughly when the customers need it, where they need it, in the form they need? Does it fit in well with current demand curves, electricity grids, gas pipelines and other methods of supply etc.?

Deliverability of the Technology. Is the technology modular and easy to deploy in whatever sizes are required or are special sites needed? How much R&D will be needed to bring it to the market, and how much intervention will be needed to encourage take up, to obtain local planning approvals, etc.)?)?

The Need for EU-wide R&D. Is there a need for the Commission to support and/or coordinate the work, or can individual Member States or companies do the work satisfactorily? EU-wide effort may be needed because of the scale and cost of the work, because EU-wide standards or agreement (often about safety and risks) are necessary, or because a problem in the technology is intractable and needs EU-wide effort to maximise the chance of solving it, etc.

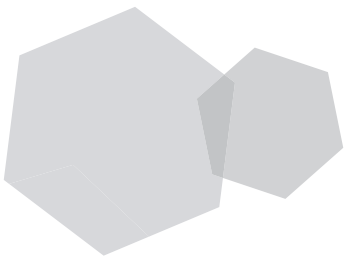
Secondary (spin-off) merits. Are there significant export markets or non-energy benefits which should be considered.

Special factors. Are there other significant factors, such as the need to employ an especially skilled workforce, known public antipathy, etc.

Each synthetic report, containing SWOG's appreciation of and conclusions about each of the technologies, includes a matrix showing our evaluation against the common set of criteria. It is important to stress that these reports are the collective view of a group of energy experts who cover the whole energy field and have been forced to apply common evaluation tests to everything under consideration.

In this way, SWOG has selected the R&D tasks it believes are important, but it has not prioritised within its selection; all tasks identified are important. Nor has it considered in detail the optimum timing of particular R&D, or the possible competition between different new technologies as they are introduced into the energy system. This is, in part, because it believes that we cannot afford to neglect any energy technology with high potential, even for the time being and even if the likely time to its fruition is long. The inertia of the energy system is so great that little which is likely to prove important can be left until much later. Also, it believes that the precise timings of real, persistent shortages of oil and gas, and/or of a worldwide recognition that global warming needs much more serious action than has been taken so far, are themselves very uncertain. Thus, the current high price of oil could be the beginning of persistent shortages but may be just a temporary problem. Nevertheless, SWOG expects to return to the issue of timing in later work.

Nor has SWOG considered in any detail where and by whom the R&D it recommends should be done. It is clear that universities, industry and energy laboratories will all have a role to play. The parallel ERA group has considered in much more depth how those R&D tasks that need EU-wide involvement can be carried out and it will report shortly.



V. CONVERTING USERS TO BROADLY SUSTAINABLE ENERGY

New energy technologies will have to be widely used to have a significant impact. However, energy is a commodity good, sold to most domestic, commercial and industrial users in the same forms, namely electricity, natural gas or various refined liquid hydrocarbons. Provided the supplies are reliable, users cannot easily differentiate between one source of electricity and another, or between one gas supply and another, except on price. The easiest and surest way to cause consumers and suppliers of energy to use a new energy source is therefore to make it cheaper than alternatives so, for that reason, the cost of energy is a crucial parameter for all technologies.

In a free economy, the greater the economic driving forces the faster the energy system will change. Thus, the UK electricity generating companies switched en masse and very quickly from coal to gas for electricity generation during the 1990s because surplus North Sea gas was available from the UK continental shelf at low prices, and very efficient combined-cycle gas turbine plant was also available to magnify the savings. But if there are no economic driving forces or they are negative, the need to change will be ignored or even resisted by most users. This poses an enormous problem for democratic societies in introducing new, CO₂-free, non-oil-or-gas energy technologies if they are less convenient and/or more expensive than those we need them to supplant. Simply appealing to consumers' better nature to do what is desirable for the environment or for energy sustainability is rarely very effective.

Governments can tilt the economic playing field of course. France has achieved a very much higher fraction of fuel-efficient diesel cars than most EU countries via taxes which differentiate against gasoline fuel. Denmark has achieved a high level of wind-generated electricity through generous support subsidies for that industry. Even simple compulsion is sometimes possible, provided the additional costs forced on users are not too obvious, can be passed along the supply chain easily and are therefore broadly acceptable. The best examples here are the regulations requiring sufficiently high levels of insulation in all new buildings.

But subsidies, taxes and compulsion are fraught with problems. National or even regional taxes on the energy supplied to industries having to compete in a global market economy can easily cause the manufacture or service to move elsewhere. For subsidies, taxes or compulsion to work in a democratic, free-market economy, the majority of the population must understand and accept the reasons for it and others elsewhere in the world must co-operate.

The importance of economic potential

SWOG therefore believes that those technologies that have good prospects of providing energy at (or not too much above) current energy prices are especially important since they have the best chance of being widely used. It is essential that the maximum possible R&D efforts are made to improve their competitiveness and, if possible, to make them truly competitive. Wind energy is one example, currently not competitive without support but which could conceivably become so with successful development of larger, more flexible turbines.

Similarly, there are great potential benefits to be obtained in trying to solve any safety or environmental pollution problems associated with those technologies which are already



economically viable or close to it, but are not acceptable for some other reason. Thus, nuclear fission is competitive (or close to it) at current costs and prices, and strenuous efforts should be made to resolve the difficulties over safety and waste disposal which currently hamper its use. Cleaner coal technologies with CO₂ sequestration could also be extremely valuable. In both cases, the major improvements in technology and public attitude which are required are probably beyond the capabilities of the present nuclear and coal equipment vendors in Europe.

In contrast, SWOG believes there is not much point in putting a large *development* effort into those technologies that seem likely only to provide energy at very high prices *until* more fundamental research has identified ways in which they might become truly competitive. SWOG believes the European Commission has an important role in tackling research which is too risky or too far from the market for industry to sponsor; the requirement here is to do the minimum amount of work required to improve the technology to the point where it can conceivably become competitive, and industrial development can take over (solar photovoltaics, for example).

Finally, if a technology is already economic and well used then those incremental improvements which will allow its wider use can probably be left to equipment suppliers who will respond quickly to the market opportunities provided by increases in energy prices. SWOG believes that wood and waste burning fall into this category.

VI. KEY EUROPEAN ENERGY R&D TASKS

Against this framework of thought, SWOG has evaluated the eight technologies it initially selected and has drawn the following conclusions with respect to the key R&D tasks necessary to take each forward. Its conclusions are summarised below and set out in more detail in the eight annexes to this report:

Biomass energy

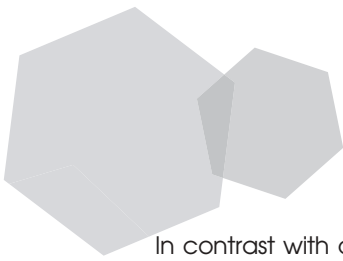
Biomass energy, that is solar energy captured by plants through photosynthesis and fixed in carbohydrate material, is the traditional energy source of much of mankind. It can be used as plant material direct from the field or in the form of agricultural (including forest industries), household and industrial wastes. Among the non-fossil energy technologies in prospect for the future, only biomass produces solid, liquid and gaseous fuels which can be used as, or easily transformed into, fuels for transport, electricity generation and heating applications.

Simple biomass combustion technologies are already competitive with oil in those rural areas where wood residues are available nearby and can be burned in small, decentralised plants, and with oil and gas in urban areas where the combustion of municipal wastes saves the cost of transport to and disposal in scarce landfill sites. SWOG sees little contribution which EU-wide R&D can make to increase this 'conventional' use, although manufacturers will doubtless continue to improve boilers, fuel/feed systems, etc. and should be encouraged in the usual ways, via tax relief on R&D, measures for market deployment, etc.

However, the available biomass resource in most EU countries is limited, and ways should be sought to maximise it. EU-wide R&D should aim at designing plants optimised for energy use, looking for a better trade-off between high yield, fertiliser requirements and limited environmental impact. It should also encourage a few local communities to demonstrate, with currently available technology, the complete biomass supply chain in action. Converting biomass to liquid (BTL) fuels is potentially very important for two reasons. It not only offers the prospect of retaining liquid chemical fuels for transport without increasing atmospheric CO₂, but also the possibility of a global trade in biomass-derived liquids, not really possible with solid biomass itself. Because of this potential of BTL to provide liquid fuels indigenously or from a wide range of external sources, SWOG believes that EU-wide R&D is important, in particular trying to find biological processes for converting the ligno-cellulose parts of woody plants to liquids. The alternative approach of using chemical or biological processes to separate liquefiable sugars and starches from solid lignin, which can then used as a solid fuel, also needs to be pursued. R&D on optimising the design and operation of conventional BTL plant for the different biomass feedstock which might become available in or to the EU would also be useful in order that the conversion technology and costs of BTL fuels might be reduced or at least become less uncertain.

Cleaner use of coal

Fossil fuel technologies are the workhorses of the current energy system and are widely expected to remain so for at least the next few decades, despite the trend for oil and natural gas to become scarcer and more expensive and Europe's increasing dependence for their supply on imports.



In contrast with oil and gas, the resources of coal, heavy oils, tar sands, etc. (SWOG uses 'coal' as shorthand for all these less convenient and more polluting fossil fuels) are large and expected to last for several hundreds of years. They are cheaper and more widely distributed than oil and gas, both in Europe and around the world. Therefore, SWOG believes that an important challenge for the 21st century is to find better ways of making use of these relatively abundant, widespread, cheap, and widely used fossil fuels whilst minimising, preferably eliminating, the pollution their combustion causes.

SWOG recognises there are three distinct approaches to meeting the challenge of making the use of 'coal' more attractive and less polluting. The first is simply to improve the efficiency of the current methods of using fossil fuels, including coal. Thus, SWOG concludes that the European Commission should support and coordinate R&D on high-temperature materials and generic component design, which will ultimately enable boilers, turbines, and internal combustion engines to achieve higher efficiencies. SWOG also believes that the Commission should encourage the development and demonstration of super-critical and ultra-super-critical steam generation and turbines, operating at steam temperatures of 700°C or higher, to ensure that they become available as soon as possible. Support for the systematic collection of experience in the co-combustion of fossil fuels is also important to encourage the spread of best practice.

The second general approach is to seek to deploy inherently cleaner coal-burning technologies that allow more pollutants to be captured at source. These include pressurised-fluidised-bed-combustion (PFBC), integrated gasification combined cycle (IGCC) systems, coal gasification technology more generally including hot-gas-clean-up techniques, combustions systems that make CO₂ separation easier, and chemical looping. The potential of IGCC for making carbon-free fuels deserves particular focus, offering as it does both electricity and hydrogen generation. To make progress here, SWOG underlines its recommendation in the previous paragraph for more R&D on high-temperature materials. But SWOG also recommends that the Commission supports R&D for these inherently cleaner coal-combustion technologies on an EU-wide basis, so that one or two plants of realistic size can be built and used to evaluate and improve the current technology and improve our certainty of their costs.

Thirdly, because more efficient and inherently cleaner combustion does not eliminate the problem of the large quantities of CO₂ emissions from using coal, it is crucial to develop and prove the technologies needed to separate and store a large fraction of the CO₂ inevitably produced when coal is used. Thus SWOG believes:

- that improved or new processes which can separate and capture CO₂ more cheaply in exhaust gases are urgently needed. R&D to explore new ideas should be given high priority in the EU Framework Programme;
- that proving long-term CO₂ storage must be a high priority task for EU-wide R&D in the next few years, aimed at demonstrating the safety and viability of different CO₂ storage options and eliminating any long-term risk.

Success with CO₂ sequestration will allow the EU to use a wide range of energy options which might otherwise have to be abandoned. Overall, SWOG believes that the combination of clean coal technologies with CO₂ capture and storage could result in important technologies in which European industry could have a leading role, and secure a competitive position worldwide.

Fuel cells

Fuel cells have the technical potential to convert chemical fuels into electricity and motive power at higher efficiency than is currently being achieved and with low or even zero emissions. Polymer Electrolyte Fuel Cells (PEFCs) using hydrogen as a fuel are especially promising for the huge vehicle propulsion market. Other fuel cell types, such as Molten Carbonate Fuel cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs), are more suitable for stationary applications and have the potential to generate electricity from various fuels at high efficiency together with useful, high-grade heat. SWOG therefore accepts that fuel cell technologies may well be able to contribute significantly to a more efficient and cleaner use of primary energy resources in the medium term.

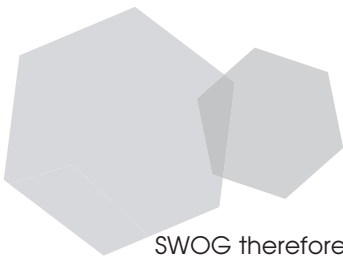
Although there have been major improvements in the last decade, multi-disciplinary R&D covering novel material technologies and system innovations are still needed to bring fuel cells to the market. The greatest long-term benefit from using fuel cells is expected to be in the huge (several 100 GW/year) transportation market, especially for powering automobiles. However, this is also the most challenging market in terms of cost and technical specifications, and SWOG believes that the search for improved fuel cell technologies should be given high priority, with cost reduction and long-term reliability the most important goals. Moreover, their widespread use in transport would require hydrogen to become a major energy carrier alongside oil, natural gas and electricity.

European fuel cell R&D should be coordinated by the Commission and targeted on achieving economically competitive fuel cell systems. R&D on improved PEFC fuel cell stacks, especially the membrane electrode assembly (MEA) subsystem, including more effective and cheaper catalysts and higher-temperature polymer membranes, is the highest research priority. Verification of new technologies and their demonstration in vehicles or other transport applications will, of course, be needed to consolidate any breakthroughs and initiate a widespread use of new technology. As for high-temperature fuel cells for stationary applications, R&D is needed on improved cell and electrode/interconnection materials as well as on cost-effective manufacturing processes and designs.

Hydrogen as a major energy carrier

Hydrogen is not a primary energy source because elemental, molecular hydrogen does not occur naturally on earth in significant quantities. It only occurs in combination with other elements, primarily with oxygen (in water) and with carbon, nitrogen and oxygen (in living materials and fossil fuels). However, when separated from other elements to form molecular hydrogen, a process requiring energy that must be provided from elsewhere, it becomes an energetic and environmentally attractive fuel. It is then a potentially desirable means of delivering energy to final consumers, freeing that final energy use from CO₂ emissions, just as electricity does. Consequently, it is often seen as an important, storable energy carrier for the future, alongside refined liquid hydrocarbons, gas and electricity.

For hydrogen to become a successful energy vector in the future, the whole supply chain from production, through transport, distribution, storage to end use, must be cost effective compared to other sources, albeit taking external costs into account. The major cost challenges for hydrogen are in production and in the end uses, especially in fuel cells.



SWOG therefore believes that high priority in hydrogen R&D should be given to developing more cost-effective production. This could be by improving water or high-temperature steam electrolysis, or by exploring schemes to generate H₂ biologically, photo-biologically or via high-temperature thermal splitting of water.

Hydrogen storage is also a serious difficulty for mobile applications. SWOG therefore concludes that strong EU-wide support is needed on R&D to pursue promising ideas for mobile hydrogen storage, since none of the currently proposed methods are truly satisfactory.

Finally, SWOG notes that a future hydrogen economy will depend on the successful development of improved fuel-cell technology. Sufficient R&D effort is needed therefore to ensure reliable and affordable fuel cells penetrate the market (see the previous section on fuel cells).

Nuclear fission

Nuclear Fission is currently an important contributor to EU electricity supplies (32% in EU-25) and has the potential to make a much bigger contribution at costs close to current prices for bulk electricity. Indeed, if the recent rises in the price of oil are maintained and filter through to gas, then nuclear electricity will be the cheapest way to make baseload electricity in the EU. However, public and political antipathy is such that its contribution will grow and become accepted as a major component of EU energy sustainability only if the following can be guaranteed:

- Safety and security in nuclear power facilities, ensuring a high-level of protection for workers and essentially no risk to the general population or the natural environment from radiological hazards caused by accidents or terrorist attack.
- Safe final disposal of the radioactive waste produced; as well as achieving:
 - optimised use of natural resources (natural uranium for the time being, possibly complemented by thorium in the longer run);
 - minimised production of long-lived, high-level radiotoxic waste.

To achieve these goals, SWOG believes that the priorities for EU-wide nuclear fission R&D should focus on innovative reactor design and advanced fuel cycles, whilst continuing work on waste treatment and disposal and on the biological effects of low radiation doses. These are the four main lines of action:

- Development of innovative power plant through the Generation IV International Forum (GIF). Priority should be given to advanced safety concepts, as well as closed-cycle, fast-neutron reactors which allow optimal use of natural resources and minimisation of toxic waste. SWOG believes that the EU collectively (Euratom) should continue to participate in GIF and should make the necessary preparations to contribute significantly to its R&D programme.
- Validation of models and technology for geological waste disposal. The Commission should provide support to ensure that each local project contributes as much as possible to Europe's understanding of this now essential activity.

- Development of better spent-fuel treatment, including partitioning and recycling processes for actinides. R&D on advanced spent-fuel treatment should be encouraged, including partitioning and recycling processes for actinides. The impact of advanced spent fuel treatment, such as partitioning and transmutation, on waste repository design and performance should be carefully assessed.
- Gaining a better understanding of the effects on human health of radiation at low doses. The effect is hard to measure because it is very small and so easily masked by other factors having no connection with radiation, such as air quality. Epidemiological studies are now unlikely to resolve these uncertainties but a better understanding of the fundamental mechanisms of DNA damage and repair should eventually do so. SWOG therefore recommends continuing research aimed at a better understanding of the cellular damage caused by radiation and its repair.

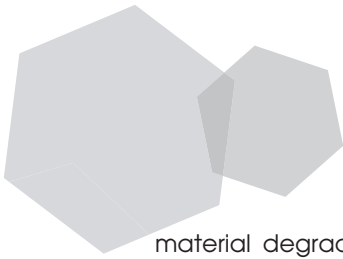
Nuclear fusion

Nuclear fusion energy has long been seen as a potentially attractive new source of electricity. It tantalisingly offers most of the advantages of fission power with even more readily available fuels and without the possibility of major reactor accidents releasing large quantities of radioactive material, and without producing very long-lived radioactive wastes. For many years even its technical feasibility was in doubt, but that has now been demonstrated with high confidence. The uncertainty which still remains is whether it will be a practical and reliable energy source, given the complexity of the technology and, in particular, whether the energy will be produced at anything like a competitive cost.

Unfortunately, because fusion technology is complex and inevitably large scale, the research is very expensive; it simply cannot be taken forward at low cost. In spite of this, indeed to some extent because of it, SWOG believes the uncertainty over its future contribution needs to be eliminated as soon as possible. Doing so will not only minimise overall fusion development costs but also clarify quickly whether fusion will or will not be a decisive energy contributor in the future, with the consequent major impact on energy R&D strategy. It is important to bear in mind that Europe has a worldwide lead in fusion and that, following its successful development, it would be in a strong position to offer fusion energy technology wherever it might be needed.

SWOG concludes, therefore, that the International Thermonuclear Experimental Reactor (ITER) device should be built as soon as possible, preferably in Europe, to demonstrate fusion's technical feasibility with certainty and gain some experience with the operation of realistic-scale fusion technology and subsystems. The project should be carried out as international collaboration to share the costs, but with the EU playing an active, leading role.

SWOG also supports the so-called 'fast-track' approach to fusion energy, now being advocated by the fusion community. This involves proving ITER-like reactors and identifying difficulties in using them at the same time as developing the materials and other technologies which will be needed for such reactors when they are used at high-load factors. SWOG therefore believes that, in parallel with ITER, a device like IFMIF (International Fusion Materials Irradiation Facility) should be built, again in an international context if possible. Such a device is needed to investigate the



material degradation caused by 14-MeV neutron bombardment, since this will be crucial to determining the practicality of fusion but cannot be tested on ITER.

ITER and IFMIF are the crucial elements of the fast-track approach to fusion, which can minimise the total development cost and the time of uncertainty over fusion energy. However, SWOG stresses that some resources must be provided for a supporting programme of core plasma physics and alternative concepts to the tokamak, as these more fundamentally oriented efforts may help to deal with problems and/or surprises in ITER or may provide the key to devices with lower costs and better performance.

SWOG acknowledges that the EU fusion programme is a prime example of an ERA as the work cannot sensibly be done by individual Member States.

Solar photovoltaics

Photovoltaic (PV) systems use semiconductor materials to convert sunlight directly into electricity. They have already proved their advantages over conventional energy sources in remote, off-grid applications and in mobile specialist devices such as watches and calculators. These applications have already created a successful PV manufacturing industry.

PV systems also have many features which are attractive for bulk energy supply, not least the technical potential to supply electricity for a significant part (up to about a quarter) of the total EU demand. Thus, the input solar energy is ubiquitous and fully sustainable; the raw materials needed for PV manufacture are very widespread; PV poses only modest safety risks to the workforce (during installation and cleaning) and none to the general public; they cause no noise or gaseous emissions when in use; when used as roofs or façades for buildings they cause little visual intrusion; their modularity makes it easy to match capacity to demand requirements; installation is usually straightforward and quick; they cannot be significantly disrupted by any political, economic or terrorist incidents. Moreover, the direct economic benefit to the owner is often in electricity that no longer has to be bought from retail suppliers at high, retail prices.

Their drawbacks are that they cannot directly meet electricity demand at night, during bad weather or in winter in the more northerly, cloudier countries of the EU, their take-up is likely to be slow if it has to be linked with replacing or refurbishing buildings and, above all, their costs are currently too high. The cost of grid-connected PV systems have certainly decreased in the last decade, to the extent that resulting electricity costs are close to retail electricity prices in favourable situations. But these costs are currently some five to 20 times higher than generating costs for conventional sources, and major further reductions are needed. A simple increase in the number of installations will certainly reduce the gap, through 'learning-curve' manufacturing cost reductions for PV modules and systems, improved reliability, longer life and higher efficiencies, although SWOG believes that more needs to be done to close the cost gap.

The current PV scene is dominated by polycrystalline or single-crystal silicon. Improved silicon components and systems are certainly possible, especially through the development of thinner cells, the better application of PV in buildings and the built environment, and the application of PV in large-scale MW-size plants. Improvements in large-scale systems, including higher efficiency contacting mechanisms and better integration with electricity grids will also be useful. SWOG sees

little contribution which EU-wide R&D can make to this 'conventional' silicon technology now in volume production, although manufacturers will doubtless continue to improve PV cells and systems and should be encouraged in the usual ways, via tax relief on R&D, measures for market deployment, etc.

However, SWOG believes that it is unlikely that crystalline or polycrystalline silicon will turn out to be the best PV concept for bulk use. Finding a more cost-effective PV technology, which lends itself better to a high-throughput manufacturing process, is the key issue for R&D. The really widespread deployment of PV energy in the grid-connected market hinges on the development of improved materials and innovative concepts for a new generation of PV systems. These might include organic or hybrid solar cells, the improvement of thin-film technology for PV materials, the further development of PV processing, and automated manufacturing technologies.

SWOG therefore concludes that the main R&D priorities are:

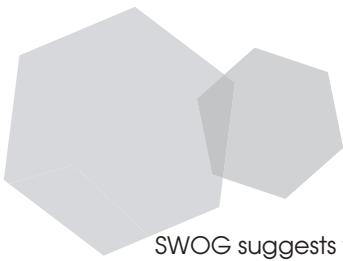
- Exploration of novel PV materials, including organics, and new production technologies.
- Novel thin-film modules and production techniques.
- Work on truly mass-producible PV modules, linking device physics with manufacturing technology and material research on promising PV technologies.

Wind energy

Wind energy is sunlight converted into atmospheric kinetic energy, via convection in the atmosphere and evaporation over oceans. It is a fully renewable energy source with very low external costs and a great potential for increased use. In the EU, by 2022, wind turbines could produce 10% or more of the expected electricity consumption. Achieving such a contribution will be a great challenge since wind energy must be competitive in the market place despite its inevitably fluctuating nature.

SWOG agrees that wind power can contribute substantially to the European energy economy, provided that further reduction in overall system costs can be realised, that a sufficient number of good sites (including suitable sites offshore) can be used, and that the external costs assigned to competitive sources are set at realistic levels and do not remain clouded with political uncertainties.

Realising wind's contribution will require medium- to long-term R&D of a kind that is unlikely to happen unless supported by public initiatives at national and EU level. SWOG believes, therefore, that EU-wide, long-term generic and scientific R&D in wind energy would be appropriate to support the sector. The necessary basic element will be the establishment in FP7 of a research programme dedicated to wind energy, with the aim of supporting R&D projects and facilitating the further development of European industry in the wind energy sector.



SWOG suggests that, among the many R&D topics necessary for wind energy, particular attention is paid to:

- a better understanding of wind resources, particularly in complex terrain and offshore, including better prediction of power outputs and the increased reliability of short-term (six to 48 hour) forecasts;
- 'fourth-generation' wind turbine technology, i.e. novel rotor concepts using 'intelligent' materials; the enabling computational fluid mechanics; new generator concepts;
- offshore installations including design, operation, and maintenance;
- grid integration, i.e. radically different and better systems and techniques for dynamic grid management based on improved systems integration, systems analysis, and control technologies.

Conclusion

These are the essential features of SWOG's work on identifying key tasks for European R&D so far. Its detailed assessments of the opportunities for the eight chosen energy technologies, together with the problems they face and the key R&D tasks needed to overcome them, are set out in more detail in the synthetic reports attached below as Annexes 1 to 8. It believes that it has covered many of the most important energy R&D issues in this present work, but not all, and therefore plans to extend its coverage to other energy technologies in 2005.

Annex 1: Biomass Energy

Background

Biomass energy, that is solar energy captured by plants through photosynthesis and fixed in carbohydrate material, is the traditional energy source of much of mankind. Before the advent of fossil fuels, our forests provided most of the fuel needed for cooking and for keeping warm in winter.

In the EU-15, wood fuel has long since been overtaken by coal, oil and gas. Biomass now provides only about 5% of EU primary energy consumption, although it is still Western Europe's most important renewable energy source by a significant margin. It is more important in some Member States than others; in Portugal it provides more than 15% of primary energy, and in Luxembourg, Finland and Sweden more than 20%.

The source of most biomass energy in the EU is still wood, burned for heat in households, district-heating plants and in industry and, primarily in Finland and Sweden, in generating plants for electricity production. However, there is a growing use as fuels from agricultural residues such as straw and domestic, commercial and industrial solid wastes. These are commonly counted as biomass since all agricultural residues and a large fraction of solid commercial and domestic waste is organic in origin. Moreover, roughly sorting municipal wastes can provide a product stream which is largely biomass. Anaerobic digestion is an attractive alternative to combustion for some wet agricultural and municipal wastes and is fairly well developed for use on farms, in the food and animal-feed industries, and in landfill sites.

Even the use of wood as a fuel is often effectively waste combustion, using thinned-out young trees or wood residues from the timber and paper industries. This point is significant because collecting biomass fuel as part of some other essential activity (the disposal of municipal wastes) or a profitable one (the production of timber, wood products and paper) greatly improves the economics of its use, and has enabled the biomass contribution to EU energy supply to remain at the 5% level without much subsidy.

Although the burning of wood or other biomass does release CO₂ into the atmosphere, it is generally accepted that biomass fuels are CO₂ neutral and do not contribute to global warming. This is because, in properly managed forests in a dynamic equilibrium, new biomass growth recaptures the same amount of CO₂ as is released in its combustion. In the past, wood burning in simple stoves was wasteful of energy and led to large emissions of CO and other pollutants, but modern boilers have greatly improved efficiency (up to 90% at design output) and lower discharges (less than 0.2 gram CO per m³ exhaust).

However, biomass is largely carbohydrate (C_xH_yO_z), is often slightly wet and consequently has a much smaller energy content (13 - 20 GJ/tonne) than oil (C_xH_y: 45 GJ/tonne) and somewhat smaller than coal (CH_{0.7}: 25 - 30 GJ/tonne). In volumetric terms, the comparison with oil and coal is even less favourable since much of the wood is in the form of lightly packed pellets or chips, and this makes the movement of wood fuel over large distances rather expensive.

The current annual production of heat from biomass in the EU is about 1.8 EJ and of electricity about 22 TWh, the latter equivalent to only 80 PJ delivered electricity but 0.25 EJ or so in primary energy terms.



The potential

The potential for an increased use of fuel wood from existing forests in the EU-15 is significant but not enormous. For example, in Austria the resource is estimated at 230 PJ/year, of which some 122 PJ/year are currently used. This ratio is typical of those Member States with extensive forests. In most Member States the potential is much less, and only in Finland is the current use (94 PJ/year) a significantly smaller fraction of the potential (350 PJ/year).

However, the global potential for biomass production is estimated to be much larger; some 450 EJ/year compared with the current global consumption of 50 EJ/year and a global consumption of fossil fuels of about 350 EJ/year.

Realising the potential of biomass to contribute more to EU energy supply therefore depends on progress in one or more of four areas:

- encouraging a greater take-up of biomass fuels than is currently used, that is the combustion of wood, agricultural residues or commercial/industrial and domestic wastes for heat and/or electricity, possibly together with:
- increasing the supply of biomass in those Member States with primarily urban populations and which no longer have extensive forests to provide wood;
- converting biomass to liquids, enabling their more flexible use and economical transport over longer distances, thereby making available to the EU bio-fuels which can be used in transport and biomass which is grown far from the consumers, where growth conditions are more favourable and/or more land is available;
- supplying technology and equipment which will encourage greater use of biomass elsewhere. This will help take global pressure off other fuels which can be imported for use in the EU, will provide foreign currency for such energy imports, and reduce global warming.

Increased use of wood and wastes

As with hydropower, but unlike most other renewables, the present conventional use of existing wood and waste resources for fuel is largely without the help of subsidies. In some situations it is competitive with oil, in those rural areas where wood residues are available nearby and can be burned in small, decentralised plants; in other situations, with oil and gas, in urban areas where the combustion of commercial and municipal wastes saves the costs of transport to and disposal in scarce landfill sites. As a result, a wide range of well-developed equipment is already available and a variety of supply chains in use. SWOG sees little contribution which EU-wide R&D can make to increase this 'conventional' use, although manufacturers will doubtless continue to improve boilers, fuel/feed systems, etc. and should be encouraged in the usual ways, via tax relief on R&D, and so on. In particular, municipal waste burning will become more widely attractive when all the problems of flue-gas pollutants, heavy-metal wastes and boiler corrosion are clearly and reliably dealt with in commercial equipment. Projects demonstrating advanced technologies or supply chain concepts could accelerate progress along the learning curve. Also, gasification followed by combustion and/or a variety of co-firing options need to be demonstrated and evaluated.

An effective way to increase the use of wood or wastes would be to level the economic playing field, recognising the benefits of biomass energy to global warming by introducing across the EU a realistic carbon tax on fossil fuels burned without CO₂ sequestration. This is already being done in Denmark, where the basic cost of energy from natural gas is about 3.3 €/GJ compared with 4.6 €/GJ for wood chips, but taxes are being used to increase the cost of gas to consumers to 10 €/GJ.

Increasing biomass resources in the EU

The supply of biomass fuel in the EU could certainly be increased by growing energy crops. Perennial plants are the most attractive prospect, because they require very low fertiliser and pesticide inputs compared with annuals, and the production of these agrochemicals is very energy intensive. Perennial crops with low inputs also create a stable habitat, with the prospect of increasing the diversity of flora and fauna in an area when compared with conventional agriculture.

Grasses would have the advantage of being harvested with conventional reaping machinery. However, willow, grown on a two- to four-year cutting cycle, commonly referred to as short rotation coppice, is favoured for northern European conditions. Currently, energy crops are not economically viable but might become so in the EU if there is a continuing need to pay farmers to take agricultural land out of food production and find other uses for it.

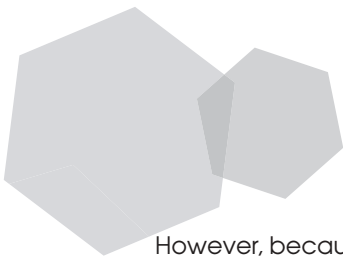
The EU-wide R&D contribution SWOG sees here should aim at breeding plants optimised for energy use, looking for a better trade-off between high yield and limited environmental impact. It also consists in making available the results of field trials and in encouraging a few local communities to demonstrate, with currently available technology, the complete biomass supply chain in action.

Biomass to liquids

The best way to transport energy in bulk is as liquid fuels, in tankers or pipelines. Liquids are also the most versatile fuels since they are easily usable in transport vehicles as well in stationary applications. The conversion of solid carbohydrate biomass into liquids has therefore always been seen as a highly desirable goal.

Making ester bio-fuels from oilseeds can certainly be done but looks uneconomical for the foreseeable future and has poor energy payback. Similarly, making ethanol by fermentation of plant sugars, although widely used in Brazil with public support, would be more difficult to pursue in the cooler, drier countries of the EU. In contrast, the conversion of whole plants, including sugars, starches and cellulose, to liquid fuel via biomass-to-liquid (BTL) processes could be widely applicable in the EU.

Various gasification and pyrolysis options are available and all the required chemistry, such as Fischer-Tropsch reactions, is well known. However, the current cost of biomass-derived liquid fuels is more than 12 €/GJ, whereas crude oil is available to the EU at 30 € per barrel, corresponding to only 5 €/GJ. Since many of the costs are in the technology rather than the feedstock, biomass liquids produced overseas are not likely to become competitive in the foreseeable future either, with crude oil often produced at less than 0.5 €/GJ.



However, because of the potential of BTL to provide CO₂-neutral liquid fuels, indigenously or from a wide range of external sources, SWOG believes that EU-wide R&D is justified here, in particular in trying to find bioconversion processes for the ligno-cellulose parts of woody plants. The alternative approach of using chemical or biological processes to separate liquefiable sugars and starches from solid lignin, which can then be used as a solid fuel, also needs to be pursued. R&D on optimising the design and operation of more conventional BTL plant for the different biomass feedstock which might become available in or to the EU would also be useful in order that the conversion technology and costs of BTL fuels might be reduced or at least become less uncertain.

Biomass combustion and processing equipment for export

The potential of biomass energy outside the EU, in Asia, Africa and South/Central America, is great. These poor countries, which use wood and agricultural wastes as fuels, would benefit greatly from using these resources more cleanly and efficiently. In lightly populated rural areas where wood or other biomass is available but coal and gas are not and oil is expensive, modest-sized, decentralised biomass generating plants will probably prove a good way of making electricity.

The boilers, electricity generating and liquifaction plants which have been or will be developed for EU use should have significant markets overseas if they are good enough and competitive. SWOG does not see the need for an EU-wide R&D programme to achieve this, but the Commission should encourage companies to adopt best practice by providing good information and to develop better products, aided by tax relief on R&D, export credit guarantees, etc.

Evaluation against standard SWOG criteria

SWOG's evaluation of biomass energy against its standard criteria is given in table A1. If energy prices were to rise significantly or large carbon taxes were introduced, the additional use of bio-fuels could be substantial, in the range of 5-10% of EU energy demand, without dramatic technological breakthroughs. Cheaper and more effective processes for converting biomass to liquids, or much larger increases in conventional energy prices, would allow an even bigger contribution.

Table A1: Biomass energy against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	small additional (but a few % of EU demand if fossil fuels carry a carbon tax) substantial - an additional 5-10% of total demand probably large - from EU and imports
Health and Safety Impacts to work force to public	good - similar to agriculture excellent
Environment Friendliness locally global warming	good - with modern equipment good - but needs careful monitoring over life cycle
Input Sustainability	excellent
Security of supply	excellent - significant indigenous supplies and no imports from Middle East
Compatibility with EU needs	fair - fuel storage is easy but energy transport to urban areas is not
Deliverability	fair - some new infrastructure required
The need for EU-wide R&D	good - need for long-term research and to spread best current practice
Secondary (spin-off) merits	excellent - major markets for equipment outside EU
Special Factors	excellent - strong public support

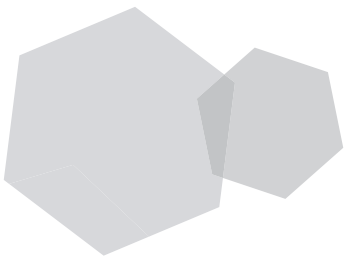
Sources of information and data

Affordable Bio-Energy Technologies, by Gerhard Faninger and Iacovos Vasalos, AGE SWOG 2003-6-41a

Bio-energy options in Europe, by Josef Spitzer, Joanneum Research Graz, Austria, AGE SWOG 2003-6-41c

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Renewables for Power Generation, 2003 edition, section 5 Biopower, International Energy Agency, Paris.



Annex 2: Cleaner Use of Coal

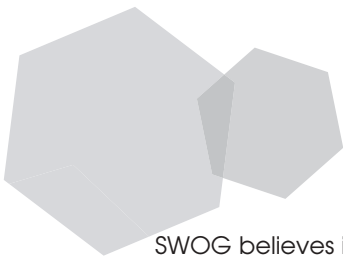
Background

Coal is fossilised biomass. Carbohydrates and fatty materials, originally synthesised from carbon dioxide and water by ferns, mosses, etc. using solar energy, were converted into peat. Then, by the action of geological heat and pressure over tens or hundreds of millions of years, the peat was converted into the dense mixture of carbon, aromatic hydrocarbons and other organic chemicals we call coal. Mineral clays, sulphides and chloride compounds are frequently present too, so that coal is a rather dirty fuel, emitting a range of pollutants when burned and leaving an incombustible ash.

Coal has probably been used in Europe since late Roman times but it is first referred to around 1200AD by a monk, Reinier of Liège, who wrote of a “black earth, very similar to charcoal, used by metalworkers”. The scale of its use was limited until the early 18th century when Abraham Darby in England developed methods of using coke made from coal in blast furnaces for making iron. The coal-burning steam engine followed, leading to a rapidly growing demand for coal. Coal took over from wood as the most important fuel in Europe and powered the Industrial Revolution until some way into the 20th century when, in turn, it was overtaken by mineral oil and, more recently, by natural gas.

Oil and gas are cleaner fuels than coal, and easier to transport and use, but coal is cheaper and globally more abundant. Currently, about 5 billion tonnes per year are used, and IEA Coal Research estimates that known global coal reserves are about 1 trillion tonnes, enough for 200 years at current rates of use. Unlike oil, where reserves are concentrated in the Middle East, coal reserves are much more widespread, with 25% in the USA, 16% in Russia, 11% in China, 11% in Europe and 9% in Australia. There are also other fossil fuels, such as tar sands, which are less well known than coal but have some of its characteristics. They usually share with coal its geographic diversity but also its impurities, hence the pollutants produced when they are burned.

An important energy challenge for the 21st century is to find better ways of making use of these relatively abundant, widespread, cheap and widely used fossil fuels whilst minimising, preferably eliminating, the pollution their combustion causes. We use the phrase ‘cleaner use of coal’ for convenience but much of our consideration applies equally to tar sands and heavy petroleum oils. Meeting strict emission standards in dealing with SO₂, NO_x, heavy metals or toxic aromatic compounds; dealing effectively with dust and ashes left after combustion; above all, dealing with the CO₂ produced, all pose a real challenge. The emission of CO₂ is particularly difficult when using coal because so much is generated for each unit of energy produced. The combustion of lignite creates 111 kg CO₂/GJ and hard coal 92 kg CO₂/GJ, compared with 78 kg CO₂/GJ for oil and only 53 kg CO₂/GJ for natural gas.



SWOG believes it is useful to keep in mind three distinct approaches to meeting the challenge of making the use of coal more attractive and less polluting:

- simply improving the efficiency of the current methods of use by modernising or replacing old plants;
- developing those inherently cleaner technologies (e.g. IGCC, PFBC, etc.) that allow more pollutants to be captured at source;
- developing and proving the technology needed to separate, capture and sequester (store almost indefinitely) a large fraction of the CO₂ that will inevitably be produced when the energy content of coal is used.

Improving efficiency

The efficiency with which useful energy is extracted from fossil fuels has increased enormously over the last three centuries, usually incrementally but with occasional dramatic improvements. Thus, James Watt did not actually invent the steam engine – Savery, Newcomen and others had developed steam engines for pumping water from mines some 70 years before – but Watt is justly recognised for inventing a major improvement, the separate condenser, which made the early steam engines dramatically more efficient and hence much more useful. In a real sense, it was Watt’s efficiency improvement that made Europe’s Industrial Revolution possible! Similarly, Diesel’s realisation that injecting fuel after compression in internal combustion engines would allow higher compression ratios and hence higher efficiencies was another step change, although less dramatic in practice because the new technology was more difficult to use.

A range of heat engines, using different thermodynamic cycles, are now in use for converting fossil fuels to motive power and electricity: Rankine (steam) cycle engines in electricity generating plant, the Brayton (gas-turbine) cycle in aircraft and power plant, and Otto and Diesel cycles in road vehicles, with various combinations also being used. Fuel cells are also a way to use chemical fuels efficiently. Completely new engines or further dramatic improvements are now rather unlikely, but the process of incrementally improving efficiency still goes on but has some way to go and will undoubtedly be carried primarily by vehicle, power plant and aircraft engine manufacturers. The world average efficiency of electricity generation from fossil fuels is about 30%, compared with the EU average of 35% and about 50% expected to be achievable from 2010 in advanced coal-fired plants. Because the worldwide fleet of coal-fired power plants will remain one of the most important contributors to electricity generation, it is crucial to improve their efficiency, both by modernising older units and constructing more efficient new ones.

Improved efficiency in converting heat to work comes from increasing the temperature at which the products of fuel combustion enter the heat engine and/or reducing the temperature at which they leave. The exit temperature must always be somewhat higher than ambient, but in practice it is often much higher still when generating mechanical power and electricity because of the characteristics of the thermodynamic cycles used to convert heat to work. It is the case that, if the hot exhaust from such engines can be used for space or process heat (Combined

Heat and Power - CHP), the overall energy efficiency can be as high as 90%. Unfortunately, these high efficiencies can be achieved only when the heat and power demands match very well most of the time – since this is rarely the case, one has to consider achievable average values rather than the theoretical optima when deciding whether to use CHP technology. Moreover, using CHP with the large central power plants needed for good pollution and CO₂ control when burning dirty fuels is rarely economical anyway, because of the high cost of distributing heat over significant distances.

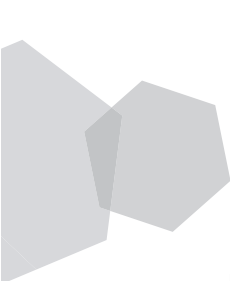
However, in contrast with thermodynamically constrained exit temperatures, very much higher input temperatures are possible, but they always depend on having materials which can withstand more severe conditions. Boiler tubes or turbine blades must be sufficiently strong when very hot and also resistant to corrosion, abrasion and creep at high temperatures; coatings and the bonding of dissimilar materials are often crucial. These are cross-cutting technologies, often valuable in many applications and sometimes beyond the capability of individual equipment manufacturers. SWOG concludes, therefore, that the EU should support and coordinate R&D on high-temperature materials and generic component design, which will ultimately enable boilers, turbines and internal combustion engines to achieve higher efficiencies.

Since coal is already the most widely used fuel for electricity generation, with pulverised fuel (PF) boilers with steam turbine power plants dominating that market, there is much to be gained from improving the efficiency of these 'conventional' plants. Achieving higher input temperatures in Steam Turbines with Supercritical Steam (STSS) is the obvious way forward and SWOG believes the Commission should support the development and demonstration of STSS power generation to ensure it becomes available as soon as possible.

Another important set of technologies involves the co-combustion of more than one fuel. Coal may be mixed with biomass, wastes and/or with oil and/or gas. Since impurities and combustion conditions when burning these mixtures will often determine the pollution caused by the plants and the lifetime of key components in them, SWOG concludes that the Commission should support the systematic collection of experience in co-combustion and hence encourage the spread of best practice.

Inherently cleaner coal technologies

There are several other 'combustion' technologies which have been known for some time but have yet to be used, and which are potentially better at burning coal and other low-quality fuels than pulverised fuel combustion. In Pressurized Fluidised Bed Combustion (PFBC) the coal does not have to be pulverised and, although it actually burns at a lower temperature than in conventional PF steam plant, it does so at high pressure which allows a combined gas-turbine/steam-turbine cycle to be used to achieve power-generation efficiencies of around 45%. NO_x emissions are low because of the lower combustion temperature. Moreover, it is straightforward to capture SO₂ by adding dolomite (calcium carbonate) to the fluidised bed, avoiding the need for flue-gas desulphurisation. The problems with PFBC are its cost and the fact that the hot gas leaving the fluidised bed is very aggressive, making turbine life and reliability a problem. SWOG therefore underlines its recommendation for R&D on high-temperature



materials and also recommends that the Commission supports one or two development PFBC units in which new materials, component designs and manufacturing techniques can be evaluated. It also recommends that the development of hot-gas-clean-up techniques is supported. Syngas (synthetic natural gas) can also be made from coal and is, of course, a much cleaner fuel at the point of use than coal. Syngas is not competitive with natural gas at current prices, but could become so in the future if oil and gas supplies fall short of demand, driving up the gas price relative to coal. It is one of the technologies which could enter the market quickly should the price of fossil liquids and gases rise. SWOG therefore recommends that the development of coal gasification technology is continued on an EU-wide basis so that one or two plants of realistic size can be built and used to evaluate and improve the technology and reduce uncertainty about the costs.

Another approach to using coal (and other low-grade fuels), intermediate between one-step combustion and conversion to syngas, is integrated gasification and combustion (IGCC). Here, the coal is partially oxidised, usually with oxygen rather than air, and the hot coal is simultaneously used to reduce steam chemically, producing a mixture of hydrogen, carbon monoxide and CO₂, without much nitrogen. Since the hot output gas can be used to produce the hot steam required as a process input, the output is effectively a cool fuel gas, easier to clean than when hot, and then suitable for burning in fairly conventional combined-cycle gas-turbine/steam-turbine plants which are cheap, clean and very efficient.

What is more, since there need be little nitrogen involved in the initial gasification, little NO_x is generated at that stage and CO₂ separation from the fuel gas is much easier than from the exhaust gases generated when the coal is burned in air. This or similar combustion systems, using oxygen-enriched air or chemical looping (in which the partial oxidation is provided by circulating metal oxides), can increase the concentration of carbon dioxide in the flue gases and should allow more economic CO₂ separation methods (see the next section). SWOG therefore recommends the Commission supports the development of these 'CO₂-separation-ready' combustion systems.

Separating and sequestering carbon dioxide

When the energy available in coal is released for use it is inevitable that CO₂ will be produced. Moreover, as noted earlier, the CO₂ production per unit of energy produced is much larger for coal than for oil and gas – orders of a magnitude larger for coal than for renewable and nuclear energy sources. A switch from oil and gas to coal and similar fuels would allow the EU to obtain fuel from a wider range of geographical sources and make available larger fuel reserves, but it will not be 'broadly sustainable' in environmental terms unless the CO₂ produced can be prevented from reaching the atmosphere for a long period of time.

Separation of CO₂ from the other products of combustion or gasification is not scientifically difficult but seems likely to be very expensive at the scale required, particular if the coal is first burned in air, as in current PF boilers. The biggest problem is separation from nitrogen, because huge volumes of CO₂ and nitrogen will have to be dealt with. This would be much easier if the fuel could be 'burned' in solid oxide or molten carbonate fuel cells (discussed in Annex 3), where the

CO₂ generated does not contain other gases, or if the conventional combustion could include oxygen-membrane separation, but these technologies are currently far from widespread use and their costs uncertain. For a conventional PF coal-burning power plant, current estimates are that about 20% of the power output would have to be used to separate and capture about 80 to 85% of the CO₂. The output energy will therefore be around 30% more expensive than from coal plants without CO₂ separation, but the CO₂ output will still not be dramatically less than from using natural gas in combined-cycle gas-turbine (CCGT) power plants. Therefore, it seems likely that current CO₂-separation technology will find it extremely difficult to penetrate the electricity generation market unless natural gas becomes relatively very expensive compared with coal. SWOG believes, therefore, that improved or new processes which can separate CO₂ from exhaust gases are urgently needed. R&D to explore new ideas should be given high priority in the EU Framework Programme.

Having separated CO₂ from the other gases, it must be sequestered (stored for long periods of time) to prevent its reaching the atmosphere. The cost of CO₂ sequestration itself seems unlikely to be very large; the problem is to transport the enormous quantities of CO₂ involved to the storage site and make sure that the site will contain the CO₂ for long enough to prevent it increasing the atmospheric concentration by a significant amount in the foreseeable future. The amounts of CO₂ to be stored are very large, and transport and disposal must take place under high pressure. SWOG believes that proving CO₂ separation and sequestration should be a high priority for EU R&D in the next few years. Success will allow the EU to use a whole range of energy options which might otherwise have to be abandoned.

Evaluation against standard SWOG criteria

SWOG's evaluation of clean coal energy against its standard criteria is given in table A2 below. Work to improve the efficiency of coal-burning plant is almost certain to be worthwhile whatever happens to oil and gas prices, although much of it will be done by equipment manufacturers. If oil and gas prices were to rise significantly, the use of clean coal technologies could be substantial and they should be made ready for use. However, if global warming via CO₂ emissions proves to be very serious then coal use will have to be scaled back unless satisfactory methods for CO₂ separation and sequestration can be developed. Its demonstration is therefore crucial.



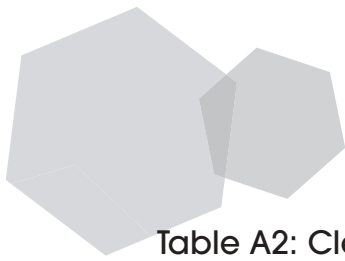


Table A2: Cleaner use of coal against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	substantial - through efficiency improvements very large extremely large - could meet the bulk of electricity and gas needs
Health and Safety Impacts to work force to public	very good - given European safety standards good - but particulate emissions are a concern
Environment Friendliness locally global warming	acceptable probably unacceptable - at current efficiencies and without CO ₂ sequestration possibly acceptable - with improved efficiency but no sequestration probably acceptable - with improved efficiency and CO ₂ sequestration
Input Sustainability	excellent - coal reserves for hundreds of years already known
Security of supply	good - coal available from wide range of sources
Compatibility with EU needs	excellent
Deliverability	good - but need to find sites
The need for EU-wide R&D	excellent - needs sequestration and other major projects
Secondary (spin-off) merits	excellent - major markets outside EU
Special Factors	difficult siting issues - for delivering coal and sequestration of CO ₂

Sources of information and data

Clean Coal Technologies, by Prof E. Kakaras, SWOG 2003-4-26

Clean Coal (Fossil Fuel) Technologies, by E. Tenckhoff and I. Vasalos, SWOG 2003-4-27 and an updated version SWOG 2003-11-28

World Energy Outlook 2000, International Energy Agency, OECD, Paris.

Annex 3: Fuel Cells

Background

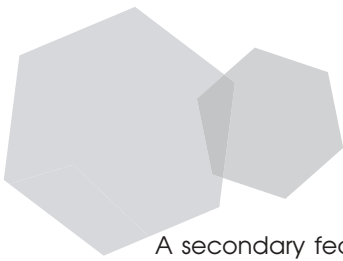
Fuel cells are not sources of energy. They are devices for converting the energy content of chemical fuels directly into electricity and hence, if required, into motive power via electric motors. They are potential substitutes for internal combustion engines or boilers/turbines, which convert fuels to motive power directly and then, if required, to electricity via generators. Like engines, fuel cells also produce waste heat that can sometimes be used. Fuel cells use hydrogen, hydrocarbons or chemicals such as organic alcohols as fuels; most use atmospheric oxygen as the oxidant although in specialist applications, such as submarines or space vehicles, more expensive oxidants like liquid oxygen can be used.

The concept is very old. In 1839, William Grove discovered the effect with hydrogen and oxygen on platinum electrodes and, late in the 19th century, Wilhelm Ostwald proposed fuel cells as substitutes for heat-engine/generators. In the 1930-40s, in Cambridge (UK), Francis T. Bacon developed the first practical fuel cells, albeit for special applications, using hydrogen and oxygen with alkaline electrolytes.

The main attraction of fuel cells for bulk energy use is that they can convert chemical energy to electricity more efficiently than they can heat engines. Typical efficiencies are 50 to 60%, compared with 30 to 40% for a diesel engine. They are especially attractive compared with heat engines in small sizes (from a few kW to 10s of MW) for distributed electricity generation and when operating at part load. Additional strengths are that they are quiet and, when using hydrogen fuel, do not generate polluting exhaust streams like most boilers and engines. However, they are still technically immature and not yet widely used because they are still more expensive and, in some respects, less flexible and reliable than conventional heat engines.

Fuel cells work by having an 'electrolyte', a material barrier through which neither the fuel nor the oxidant can pass directly but through which one or other can pass as electrically charged ions. The thermodynamically driven, usually catalytically assisted, combination of the fuel fed to one side of the electrolyte and the oxidant fed to the other side consequently generates an electrical voltage across the electrolyte which can be put to practical use.

Therefore, a key feature of all fuel cells is their electrolyte, and many are conventionally named by what electrolyte they use. Thus Phosphoric Acid Fuel Cells (PAFCs) use hot, liquid phosphoric acid as their electrolyte, which allows hydrogen ions to pass through it; Solid Oxide Fuel Cells (SOFCs) use very hot solid yttrium/zirconium oxide electrolytes, which can pass oxygen ions. Polymer Electrolyte Fuel Cells (PEFCs; sometimes referred to as Polymer Electrolyte Membrane fuel cells - PEMs) use polymers through which hydrogen ions can pass; Molten Carbonate Fuel Cells (MCFCs) have molten carbonate electrolytes through which oxygen-containing ions can pass. The ease with which the ions can pass through the electrolyte is a crucial parameter; its intrinsic electric conductivity must be around 1 Siemens cm⁻¹ to be of much practical use. The electrodes are also very important in this respect if the current-carrying capacity of the cell (or its lifetime) is not to be limited by electrodes rather than the electrolyte.



A secondary feature is how easy it is to use conventional, carbon-containing chemical fuels. In fuel cells such as PAFCs and PEFCs, whose electrolytes pass hydrogen ions from the fuel side to the oxidant and which usually means they operate at reasonably low temperatures, carbon-containing fuels first have to be 'reformed' in a rather complicated step to produce relatively pure hydrogen to feed to the fuel cell. In contrast, in SOFCs and MCFCs, whose electrolytes operate at high temperatures and pass oxygen (or oxygen-carrying) ions from oxidant to fuel, some oxidisation of the carbon content of the fuel can take place within the fuel cell itself so reforming the fuel is a much easier task.

The potential

The potential applications for fuel cells are many – wherever fossil fuels need to be converted into electricity or motive power with high efficiency. Typical fuel-cell efficiencies are around 50% but overall generation efficiencies of SOFCs and MCFCs, which operate at high temperatures, can be increased to about 70% if they are pressurised and their hot exhaust gases fed to a 'bottoming-cycle' gas turbine. Fuel cells can even be used in applications where oil or gas are burned for low-temperature heat, since making electricity first which can be sold for electricity-specific applications at the same time as making the required heat will often improve the overall economics of the system. The modularity and quietness of these applications are very attractive.

Furthermore, if renewable or nuclear energy sources of electricity become more widely used and can produce hydrogen fairly cheaply off-peak (whenever electricity demand is less than their output), then fuel cells will be front-runner devices for using that hydrogen. With hydrogen fuel, the low-temperature fuel cells would be able to shed the cost and complexity of the reformer while conventional engines would have increased complexity to work with hydrogen fuel.

However, higher conversion efficiency only brings an economic benefit for the user if the product of the price of fuel, the load factor and the efficiency improvement of the fuel cell compared with the conventional engine is high enough to offset the extra capital cost of the fuel cell amortised over its useful life. Thus, PAFCs are the best developed fuel cell type, with pre-commercial 200 kW units now on trial, but their costs remain much too high, at about 4 €/W, and their lifetimes too short, at about 50 000 hours, to compete in the market place at current fuel prices, even in high load factor applications. In comparison, combined-cycle gas turbines cost around 0.5 €/W for units around 100 MW, have efficiencies almost as high as fuel cells, and much longer useful lives, while gasoline engines in cars cost only about 7€ cents/W.

Partly as a consequence, early applications for fuel cells were often based on advantages other than efficiency. Developments of alkaline fuel cells (AFCs) have already been used effectively in space and submarines, where lightweight and zero emissions, respectively, are highly valued, but they have little prospect of use in the bulk-energy market. Indeed, AFCs, which are also sensitive to CO₂ in the air, may lose both existing and new specialist markets to hydrogen-fuelled PEFCs and Direct Methanol Fuel Cells (DMFCs) which also operate at low temperatures. One or other type seems likely to find new profitable applications in flashlights, laptop computers and mobile phones, so R&D aimed at grasping these commercial opportunities may well be sensible. These applications have good market prospects and should

be helpful in introducing fuel cells to users. However, only tiny amounts of energy are involved and SWOG does not believe any EU-wide energy R&D in this is justified.

Stationary applications

Beyond these special applications, the next most likely market for fuel cells is that of stationary electricity generation, where load factors can be high and the market potential is estimated to be a few 10s of GW/year for distributed power units up to 1 MW. Because of their high and difficult-to-reduce costs, limited lifetimes and modest efficiencies, attention has currently shifted away from PAFCs. High-temperature SOFCs and MCFCs, which have better efficiencies and need simpler reformers, are now thought to offer better prospects for stationary applications, except for very-small-size applications when PEFCs are preferred. SOFCs and MCFCs also offer intrinsic separation of CO₂ from nitrogen if the former needs to be sequestered (see Annex 2 on the Cleaner Use of Coal).

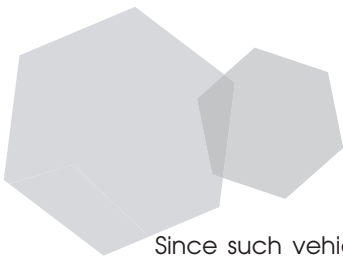
However, MCFCs and SOFCs are not as well developed or tested as PAFCs, and significant further improvements in their costs and lifetimes must be achieved if they are to penetrate the electricity generation market. Planar and tubular-design SOFCs are fairly well developed but current installations aggregate to only about 100 kW. MCFCs are also being developed for co-generation of electricity and heat but, once again, the unit sizes are currently fairly small (up to 250 kW) and the costs are currently not competitive. But the functionality and high efficiency have been demonstrated successfully and larger (1 MW) units are being developed.

SWOG therefore recommends that R&D focused on materials and manufacturing processes for these high-temperature fuel cells is supported, with the aim of reducing costs and increasing lifetimes. Electrode/interconnection materials and the reliability of the electrolyte under temperature cycling are especially important. SWOG does not think that the Commission needs to support multi-megawatt demonstration facilities until the technologies have been further optimised and costs reduced, although realistic-scale evaluations are needed of the multi-fuel capabilities which may be important for success in specialised markets.

For residential applications, smaller units (1-5 kW) are under development. These are primarily PEFCs, fuelled by natural gas reformed to hydrogen, but SOFCs are also being tried, especially for heating, cooling and electricity. Once again, costs and lifetimes are the critical issues. In this case, SWOG thinks that small-scale demonstrations in residential/commercial applications would be useful to test the practicality of the technology in this market.

Transport applications

PEFCs are favoured over high-temperature fuel cells for mobile power units for several reasons. They have higher power densities and, in vehicles, compactness is essential. Because they work at lower temperatures they are much better suited to the intermittent operation needed for transport and have much better cold-start behaviour. They are also better suited to fast load changes and have better efficiencies at part load. In a standard driving cycle (the NEDC), the overall tank-to-wheel energy efficiency of a hydrogen-powered PEFC-powered car has been demonstrated to be about double that of a conventional gasoline fuelled vehicle.



Since such vehicles are also quiet and emit no pollutants they are often seen as the ultimate answer for personal transport. However, hydrogen-fuelling infrastructures are not yet available and the cost of fuel cell technology will have to be dramatically reduced to compete with conventional car propulsion, as long as fossil fuels remain the primary energy source for transport.

The prospects for fuel-cell-powered cars will be improved by further development but they could be transformed by a number of external factors:

- Major increases in the price of liquid hydrocarbon fuels, making the efficiency advantages of fuel cells much more important.
- The availability of relatively cheap hydrogen, not derived from fossil fuels but from off-peak electricity from renewable or nuclear sources.
- Substantial further reductions in the allowed levels of noise or emissions of organic compounds, NO_x , etc. from cars in towns and cities, which could only be met by internal combustion engines with greatly increased costs.
- Serious attempts to reduce overall CO_2 emissions to the atmosphere. Contributions from cars are a major fraction of the total emissions in advanced countries, yet on-board sequestration of CO_2 is difficult if not impossible. A move to hydrogen-fuelled vehicles may be essential to reduce CO_2 , in which case the advantages of fuel cells over conventional engines would be much greater.

SWOG therefore recommends that EU-wide R&D should be supported, especially on PEFC 'stacks', the electrochemical cells which are fed with hydrogen and air, to improve performance and reduce costs. These stacks are a small part of a total PEFC system using hydrocarbon fuels but they are crucial to the final use of hydrogen, and Europe currently relies heavily on the USA for the membrane technology.

Moreover, the auxiliary power units (APUs) which are needed to meet the ever-increasing demand for on-board electricity in modern cars and other transport vehicles such as ships, are likely to create an initial transport market for advanced fuel cells, not dependent on a hydrogen fuel infrastructure. Here, fuel cells could provide the several kW likely to be needed in future vehicles more cleanly and with so much greater energy efficiency than the conventional technology of internal combustion engine plus alternator/rectifier that it will probably make economic sense to use them before fuel cells are ready for the main transport applications.

SWOG thinks that reformer development, although necessary for these applications, is less important than the stack R&D recommended above, given the tough competition PEFCs will face if their energy source is hydrocarbon fuels. High-temperature fuel cells would need substantial improvement with respect to power density as well as cost before they could conceivably be used in trucks, buses and taxis, let alone private cars.

Evaluation against standard SWOG criteria

SWOG's evaluation of fuel cells as energy converters against its standard criteria is given in table A3 below. In reality, they are not yet as attractive as their basic characteristics of high efficiency, low pollution and low noise might suggest, because of their currently high costs and limited lifetimes. SWOG believes that high-temperature fuel cells will probably find uses in distributed stationary power generation if they can be improved somewhat. Low-temperature fuel cells seem likely to find only niche markets in stationary and transport applications unless hydrogen fuel becomes widely available.

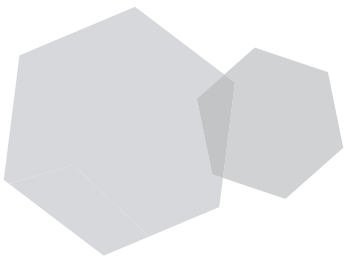
Table A3: Fuel cells against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	nil uncertain - large if R&D goals are achieved probably large in the long term
Health and Safety Impacts to work force to public	excellent good
Environment Friendliness locally global warming	excellent - few conventional pollutants and little noise good - due to better conversion efficiency - excellent - with hydrogen
Input Sustainability	fair - good if hydrogen fuel became available
Security of supply	fair - good if hydrogen fuel became available
Compatibility with EU needs	good
Deliverability	excellent - modular units
The need for EU-wide R&D	very good - may prove essential for CO ₂ -free transport
Secondary (spin-off) merits	fair - export opportunities but US and Japanese competition
Special Factors	good - strong public support expected

Sources of information and data

Report on Fuel Cells, by Wolfgang Dönitz, AGE SWOG 2003-6-39a

Report on Fuel Cells, by Wolfgang Dönitz and Jürgen Garcke, SWOG 2003-6-39b.



Annex 4: Hydrogen as a Major Energy Carrier

Background

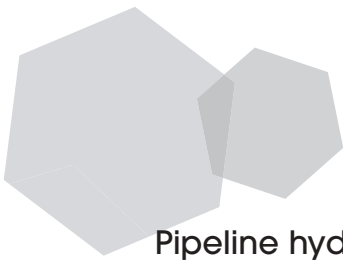
Hydrogen is the simplest and lightest of all the chemical elements and the commonest material in the universe. It is not a source of energy on earth because it only occurs naturally here in combination with other elements, primarily with oxygen (in water) and with carbon, nitrogen and oxygen (in living materials and fossil fuels). However, when separated from these other elements to form molecular hydrogen, a process requiring energy that must be supplied from elsewhere, it becomes an energetic and environmentally attractive fuel. It can be burned (or combined with oxygen in a fuel cell) without creating CO₂. Like electricity, it is a very clean fuel at the point of use although, like natural gas, it can form explosive mixtures with air.

Hydrogen is already widely used in the chemical industry and, even as a way of delivering energy to general consumers, its use is not new. The 'town gas', made by heating coal and used widely in Europe before natural gas, became available in the last half of the 20th century, was a mixture of hydrogen and carbon monoxide with various impurities. Similarly, the 'water gas', once used by the chemical industry and produced by passing steam over hot coke, was also a mixture of hydrogen and CO. These fuels were highly poisonous because of the CO in the mixture, but hydrogen itself is not toxic.

Making pure hydrogen from ordinary water is straightforward, provided electrical energy or high-temperature heat is available. Many renewable and nuclear energy sources, expected to be more important in the future, do produce electricity and it follows that hydrogen manufacture could provide the means of using some of their output when not all of it is needed at the time and place of its production. However, at the present time, electricity is almost always better used directly and most hydrogen is made by 'reforming' natural gas rather than by electrolysis.

Nevertheless, since hydrogen can be made from water by electricity and subsequently used in fuel cells to produce electricity at any point of need, hydrogen and electricity are effectively inter-convertible. Using this inter-convertibility could allow intermittent renewable energy sources, such as wind or solar photovoltaics, to provide a more reliable output and low-fuel-cost nuclear power plant to be used at maximum load factor, even when not all their electricity output is needed.

Hydrogen is therefore a potentially important energy carrier of the future, a means of delivering energy to final consumers, desirable if only because it frees that energy use from CO₂ emissions just as electricity does. Currently in the EU, energy is carried to its final customers predominantly as liquid hydrocarbon fuels (gasoline, kerosene, diesel fuel and heating oil, 48%), natural gas (methane, 23%) or electricity (20%), with small amounts of solid fuels, biomass and direct heat also being used. Hydrogen could, in principle, replace all these carriers apart from the electricity, although prodigious amounts of hydrogen (some 200 Mtonnes per year) would be needed to replace the roughly 30EJ of energy (around 670 Mtonnes oil equivalent) currently being delivered in Europe as liquids or gases. Even in the electricity supply system the hydrogen/electricity inter-convertibility could be valuable.



Pipeline hydrogen gas and stationary applications

The easiest way to use hydrogen would be as a gaseous fuel delivered by pipeline for stationary applications, either mixed with or replacing the piped natural gas (methane) which currently provides 23% of delivered energy in the EU. Hydrogen is inherently more energetic than methane (142 MJ/kg if burned in a condensing boiler compared with 56 MJ/kg) but the gas is also much less dense. The energy carried per unit volume of gas is therefore actually smaller (13 MJ/m³ for hydrogen compared with 40 MJ/m³ for methane) but, since hydrogen flows more easily in pipes than methane does, the energy-carrying capacity of a hydrogen pipeline is about 80% that of the same pipeline carrying natural gas at the same pressure.

Technically, it should not be difficult to convert natural gas pipelines and gas-burning appliances to hydrogen. However, the prospects for this happening in the foreseeable future are poor because most hydrogen is currently manufactured from methane, a process that uses up some of the energy content of the natural gas and converts some of its carbon content into CO₂ which is released to the atmosphere. Conversion of existing methane pipelines to hydrogen made primarily from methane would achieve nothing environmentally, unless the CO₂ released during production is sequestered, and would significantly reduce overall energy efficiency.

SWOG therefore believes that it will make economic and environmental sense to pipeline hydrogen only when other methods of producing hydrogen, such as renewable or nuclear-driven electrolysis or hydrogen from coal, become relatively cheaper than hydrogen from methane reforming. Moreover, even replacing methane with hydrogen from coal would only mitigate the release of CO₂ into the atmosphere if a large fraction of the CO₂ generated from the coal at the hydrogen-manufacturing plant is captured and sequestered. A prerequisite for pipeline hydrogen is therefore sufficiently cheap renewable or nuclear electricity or clean-coal energy with CO₂ sequestration; none is yet available and will not be for the foreseeable future.

Furthermore, methane (CH₄) is already a hydrogen-rich fuel compared with coal (CH_{0.7}) and oil (CH₂), and its combustion currently produces only a minor part of our total CO₂ emissions. It follows that the environmental benefit which would come from replacing piped methane with piped hydrogen, measured in the fractional reduction in overall CO₂ emissions, would be small as long as large quantities of coal and oil are burned elsewhere in the overall energy system. Methane is also relatively more abundant and more widespread than oil, so that issues of input sustainability and security of supply are not as pressing for natural gas as for oil.

SWOG therefore believes that EU-wide R&D on pipeline hydrogen is not necessary at this time and that demonstrations of its use are not yet justified. Some small-scale research work focused on the potential problems of conversion from methane to hydrogen would be sensible, to ensure that:

- a good understanding of hydrogen embrittlement of pipeline steels is available;
- hydrogen-burning appliances can achieve high levels of safety, despite the wider range of hydrogen/air compositions which are explosive (although the 4% lower limit of hydrogen in air for an explosive mixture is not much less than the 5% for methane);
- the inevitable leakage of hydrogen from the pipelines and appliances will not cause harm to the stratosphere via hydrogen/ozone reactions.

Hydrogen production

It is clear that the production cost of hydrogen is a key factor in its use as a pipelined gaseous fuel, as it is for applications in transport, discussed below. SWOG therefore recommends that the Commission supports research with the objective of reducing the cost of hydrogen production, by improving electrolysis and perhaps making use of high-temperature heat. Liquid electrolysis cells need to be improved and high-temperature electrolysis of water vapour needs development. The latter is essentially a high-temperature hydrogen-oxygen fuel cell operating in reverse and can substantially boost the efficiency of hydrogen production, potentially reducing electricity consumption by 30%.

Advanced methods of hydrogen production, such as photo-electrolysis, photo-electro-catalysis and microbiological production, also need exploring. These are very high-risk but potentially high-reward areas where long-term research is essential to obtain a breakthrough. High-temperature, multi-step thermochemical cycles using nuclear or solar heat to split water are also potentially attractive but have so far proved to be too complex; new concepts are needed.

Hydrogen as a transport fuel

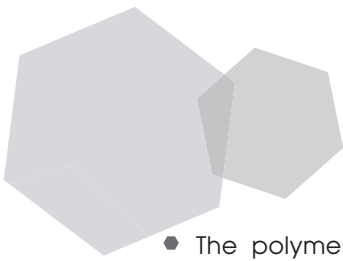
Hydrogen has great potential as a chemical fuel for transport; indeed, it is already being used in rockets and specialist vehicles. Here it offers greater advantages than in stationary applications. In terms of CO₂ emissions, its margin over conventional liquid fuels is bigger than over methane, since liquid fuels are less hydrogen rich and the capture and storage on the vehicle of the CO₂ produced by burning liquid hydrocarbons in internal combustion engines and gas turbines is thought to be practically impossible. In terms of natural resources, the oil providing current liquid fuels is in shorter supply than natural gas.

However, hydrogen is not unique in offering a CO₂-free chemical fuel for transport. A less well-recognised alternative route, which is also CO₂-neutral, is the use of liquid hydrocarbons (or similar compounds) which have been made from biomass. The growth of replacement biomass would recapture the CO₂ released when the fuel is burned. Electric battery vehicles are also CO₂-free but their range is currently markedly inferior to chemically fuelled vehicles and the lifetime of the batteries is rather short. However, hybrid vehicles with both electric batteries and a small internal combustion engine already offer a much-enhanced range of chemical fuels as well as improved engine efficiency, recuperative braking and some purely electric traction for urban use, mitigating CO₂ emissions from transport even if oil-based fuels are used.

In the giant road-transport market, it would be best to use hydrogen via fuel cells and electric motors. As well as being CO₂-free on the vehicle if the fuel is actually hydrogen, this promises energy efficiencies from 'fuel tank to wheel' of around 40% or more compared with 20% for a diesel engine.

However, in many other respects the hydrogen-fuel-cell power train is less satisfactory and is unlikely to penetrate the market significantly unless dramatic improvements are made to it. Thus:

- On-vehicle hydrogen storage is not satisfactory, currently requiring high-pressure, carbon-fibre-wrapped tanks to contain the hydrogen yet still achieving energy-storage densities and hence vehicle ranges which are much lower than simple liquid-fuel tanks.



- The polymer-membrane fuel cells, which are the only fuel cells compact enough for transport use, are currently too expensive at around 1€/Watt compared with 7€ cents/Watt for a piston engine in volume manufacture. Nor are they sufficiently reliable and long-lived yet.
- There is no hydrogen delivery infrastructure and developing one will not be easy unless a pure hydrogen (not methane/hydrogen) pipeline comes into being, which seems unlikely in the short term. Deliveries of liquid hydrogen to vehicle refuelling stations are technically feasible but would be costly, not least in energy terms.
- Just as for pipeline hydrogen, the costs of hydrogen transport fuel will remain too high unless renewable or nuclear electricity, or hydrogen from coal with CO₂ sequestration, becomes relatively cheap, or perhaps if the price differential between oil and natural gas widens substantially.

The problems with hydrogen storage and the hydrogen infrastructure can be bypassed if methane is used and reformed on the vehicle, but doing this loses many of the attractive features of using hydrogen directly: the vehicle would release CO₂; the methane reformer is bulky, expensive and inefficient at single vehicle size; and there is still the need for a new fuel infrastructure, albeit less problematic than for hydrogen.

SWOG therefore concludes that it is not yet possible to say whether hydrogen fuel, or liquid fuels made from biomass, or even the much-improved use of oil-based conventional fuels in hybrid-drive vehicles, coupled with major efforts to reduce CO₂ elsewhere in the energy system, will prove the most acceptable overall solution for transport energy in the future. The competition is currently wide open. SWOG believes, therefore, that it is too soon to provide market support for hydrogen as a vehicle fuel. What is needed now is R&D which looks for and tests better materials and new concepts for hydrogen storage (e.g. alanates or even carbon nanostructures), better and cheaper fuel cells, cheaper and more efficient methods of hydrogen production, good hydrogen detection sensors, and safety technology. Since hydrogen costs are a key issue, particular efforts need to be made to improve the economics of hydrogen production.

Hydricity

The interconvertibility of hydrogen and electricity has led to the idea of a hybrid energy carrier, hydricity. As a means of simple electricity storage, it is not currently very attractive since the energy efficiency of electrolysis (electricity to hydrogen) is about 0.7 and of fuel cells (hydrogen to electricity) about 0.5. The overall storage efficiency is therefore only about 35%, much less than for conventional pumped-water storage. Also, as long as we still have natural-gas-fired electricity generation, it will make more sense to accept surplus renewable or nuclear electricity into the electricity grids by reducing the output of gas-fired plants, effectively storing the renewable or nuclear output as natural gas.

A possible exception is that hydrogen-fuelled fuel cells distributed around Europe could provide useful grid-demand management tools. SWOG believes that the R&D needs for this use, which relate to hydrogen and fuel cells, are covered above and in the fuel-cell synthetic report.

SWOG believes that grid-management technology of this kind may well prove to be important but has yet to examine it in detail.

Evaluation against standard SWOG criteria

SWOG's evaluation of hydrogen as an energy carrier against its standard criteria is given in table A4 below. It is certainly not an energy panacea and the 'hydrogen economy', if it is ever realised, seems to SWOG to be far in the future. The economic use of hydrogen does not depend simply on increases in energy costs – only if fossil energy prices rise substantially compared with renewables and nuclear, and/or large carbon taxes are introduced, will the use of hydrogen be substantial and important.

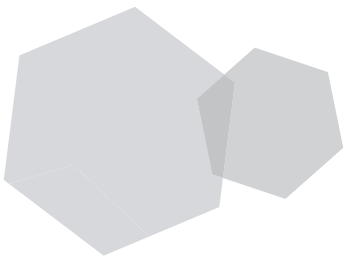
Table A4: Hydrogen energy against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	nil small - if gas becomes dear but coal or electricity are cheap and CO ₂ is taxed probably large
Health and Safety Impacts to work force to public	good - similar to chemical industry good - similar to natural gas
Environment Friendliness locally global warming	excellent - with fuel cells good - but impact on ozone layer and methane retention needs evaluating
Input Sustainability	good - provided it is made from coal, renewable or nuclear electricity
Security of supply	excellent - provided it is made from coal, renewable or nuclear electricity
Compatibility with EU needs	good - bulk hydrogen storage is easy
Deliverability	fair - for pipeline hydrogen - poor - as transport fuel
The need for EU-wide R&D	some - on hydrogen production and storage
Secondary (spin-off) merits	few
Special Factors	none

Sources of information and data

Abundant Hydrogen, by William d'Haeseleer, AGE SWOG 2003-5-36b

Large-scale use of hydrogen fuel for transportation, by Wolfgang Dönitz, SWOG 2003-5-36c.



Annex 5: Nuclear Fission

Background

The term 'nuclear fission' was coined by Lise Meitner and Otto Frisch in 1939 to describe the break-up of a heavy nucleus into two lighter ones, a process which releases large amounts of energy and several neutrons. The discovery of fission was a truly Europe-wide effort, with important contributions made by Chadwick in England, Fermi in Italy, Joliot-Curie in France, and Hahn and Strassman in Germany.

The scientists involved quickly realised that the neutrons released during a fission event could initiate more fissions and possibly lead to a chain reaction. The subsequent demonstration of nuclear chain reactions, first in uranium-fuelled reactors and later in both uranium and plutonium-based nuclear weapons, was fast and dramatic, amid the turmoil of World War II.

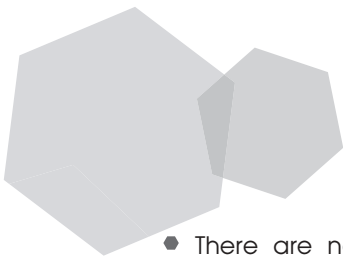
The first electricity generated from nuclear fission energy was in Idaho, USA in 1951. Large-scale production began with Britain's Calder Hall stations in 1956, but real growth did not take place until the 1960s and 70s, helped along by the two oil crises of the latter decade. Most major economies embarked on large nuclear power station construction programmes; USA, Japan, Russia, France, Germany, Spain, etc. France, in particular, moved to relying on nuclear fission for most of its electricity. Several of the new EU Member States are also major users of nuclear power.

At the present time there are some 440 nuclear power plants in operation around the world with a generating capacity of around 360 GW, with about 30 more under construction. More than 90% are light-water reactors (LWRs), with only the former Soviet Union, the UK, Canada and India having significant capacity in other types and only Canada and India not committed to LWRs. Nuclear power now provides 17% of electricity worldwide – 31% in the EU-25, and 78% in France.

The advantages

Nuclear fission is thus already a major energy source in the EU and there is no doubt that it could provide much more of Europe's energy. Like nuclear fusion, the technology offers significant advantages over fossil fuels and/or renewables:

- Uranium ores are widespread and abundant, with few competing uses and easy to stockpile. Supplies are available from many politically stable countries. In the longer run, thorium ores could also be used.
- Fission is a concentrated energy source, with modest land use and small material-feedstock requirements. Power stations can be sited on low ground to minimise their visual impact, including at the coast where the use of fresh water and cooling towers can be avoided.
- It is not dependent on diurnal or lunar cycles, nor subject to the vagaries of the weather or seasonal climate, making it well-suited for baseload generation.
- Nuclear power stations do not produce greenhouse gases or any of the air pollutants from fossil fuel combustion.



- There are no obvious technical limits to the extent to which it can be used; it could conceivably provide the lions' share of electricity generation for the whole EU, as it already does in France.
- Some fission reactor designs can generate high-temperature heat which could be used for metallurgical processes or hydrogen production, not just electricity.
- Most of the costs of nuclear fission energy are in the technology, in which Europe could easily be self-sufficient.

Unlike nuclear fusion, there is no doubt over the practicality of fission.

Fission offers mankind a huge new energy resource despite the fact that, in current reactors and fuel cycles, the energy content of natural uranium is only used to a small extent – less than 2%. Even on this basis, the 16 Mtonnes of known and 'speculative' resources of uranium are amongst the largest energy resource on earth (roughly comparable with oil reserves), and additional quantities of fissile-material ores are likely to be found if sought. Moreover, since the cost of uranium constitutes only a small fraction of the total cost of nuclear electricity, more expensive uranium could be used without harming nuclear's competitive position too much. Finally, so-called breeder fuel cycles are available and have been proven technically; they can extract 50 times more of the energy in natural uranium as well as that in natural thorium.

The drawbacks

However, despite all these advantages, in many Western countries confidence in nuclear power is low and some political parties are officially anti-nuclear. Fission energy is now seen by many people as too unsafe to use, as creating waste for which no assured disposal method is available, and as encouraging the proliferation of nuclear weapons and nuclear terrorism.

Despite some accidents in very early reactors, real concerns for nuclear plant safety only emerged in the 1970s and 80s, exacerbated by:

- The LWR accident at Three Mile Island in Pennsylvania in 1979. Although this released very little radioactivity, it almost instantly converted a billion \$ asset into a several billions \$ liability, not popular with investors.
- The accident in an RBMK-type reactor at Chernobyl in the Ukraine in 1986, which not only destroyed the reactor but also spread radioactivity across Europe.

Over the same period of time, it became apparent that the ultimate disposal of radioactive waste materials would prove very difficult because:

- Not all experts were satisfied about the safety of the disposal methods proposed over the very long times needed for the radioactivity to decay to safe levels.
- Local opposition to plans for disposal of nuclear waste in any particular locality was almost always very intense.

Other concerns also grew about the misuse of materials created in nuclear reactors. Plutonium, inevitably made in nuclear power stations, is the material of nuclear weapons, albeit not usually

at the quality required for sophisticated, high-yield warheads; and it is highly toxic. Fission was therefore accused of encouraging nuclear weapon proliferation and producing radioactive materials that could be used by terrorists in so-called 'dirty bombs'.

Finally, also in 1986, the price of competing fossil fuels collapsed, making nuclear fission (and all other non-fossil energy sources) much less competitive. As a consequence, there have been few new nuclear-power-plant orders for almost two decades. However, the prices of competing fuels are now much higher and nuclear fission is again competitive or nearly so. The question over its future is whether investor and public concerns for plant safety, waste disposal and proper care for nuclear materials can be satisfactorily answered whilst retaining sufficiently economical designs and procedures. It remains to be seen whether widely acceptable, economic nuclear fission is a realistic vision or just a pipe dream?

Carrying development forward

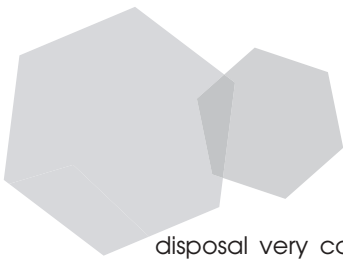
It may be that further increases in the prices of fossil fuels and/or concern about global warming will cause the public, governments and the utilities to espouse nuclear fission again because they conclude there is no realistic alternative; some commentators think so. But most intelligent and perceptive experts believe that the nuclear industry must actively address the concerns that have dogged it and be prepared to offer new designs and approaches which deal with them. So, what if anything can be done to make this obviously practical and powerful energy technology acceptable again?

The continued safety of existing power stations is a necessary condition, but not sufficient. Modern EU reactor designs (usually called 'generation II' plant) do have a good safety record, consistent with the low risk of serious accidents expected of them if construction and operation are carried out with good quality control. They should remain safe if properly maintained and operated under good safety regulation.

But major accidents are not completely inconceivable in generation II plant and 'generation III' designs (such as the Framatom-ANP 'European Pressurized-Water Reactor' and the BNFL-Westinghouse 'AP-1000' plant) have therefore sought to further reduce the risks by including passive emergency cooling features, molten-core catchers, etc. Preventing all accidents from having off-site consequences is clearly the target to aim for - it should be achieved in some generation III designs and is to be encouraged.

GIF-led generation IV designs seek even better safety, as well as improved fuel cycles which make better use of natural uranium and minimise the production of long-lived radioactive waste. GIF (the Generation IV International Forum) is an international group of governmental entities having the goal of facilitating bilateral and multilateral co-operation related to the development of new nuclear energy systems. It is a formal, government-sanctioned organisation committed to collaboratively pursuing R&D on Generation IV systems). SWOG believes that the EU should continue to participate in GIF and should make the necessary preparations to continue to participate when the paper evaluation gives way to real R&D.

Disposal of radioactive waste is perhaps the one field where scientific evaluation and public understanding are furthest apart. The scientific community has modelled geological waste



disposal very carefully and almost always concluded that it will lead to only small additional radiation doses to tiny critical groups of people in hundreds of thousands of years' time. The nuclear industry argues that it is most unlikely that these small collective doses will be significant then, but many people remain suspicious and unconvinced. Choice of actual disposal sites will inevitably be made locally, with high levels of local consultation essential, but SWOG believes the EU should provide support to ensure that each local project contributes as much as possible to Europe's understanding of this now essential activity.

A major factor in public concern over the risks of nuclear power comes from not knowing the effect on human health of low doses of ionising radiation. The effect is hard to measure largely because it is very small and so easily masked by other factors having no connection with radiation, such as air quality. Epidemiological studies are now unlikely to resolve the uncertainties and only a better understanding of the fundamental mechanisms of DNA damage and repair can do so. Such an understanding would also help target resources in protecting the public from natural and medical radiation which, for most people, massively outweigh radiation from nuclear power. SWOG therefore recommends continuing research aimed at a better understanding of the cellular damage caused by radiation and its repair.

The role of the European Union

EU-wide involvement in fission energy development is essential, primarily to ensure that Member States evolve a common understanding on the safety requirements to be set for new plant designs and on waste disposal. These requirements should preferably be common with the USA, Japan and others intending to use nuclear energy. Only then will the nuclear plant construction industry, currently trying to survive with almost no new orders, be able to justify the costs of developing and selling the new designs. However, in achieving commonality it will be important to ensure that the common standards finally agreed are based on good science. SWOG therefore believes that fission research needs EU-wide funding and coordinated attention, with resources focused on improving the technology for the future, not simply on ensuring the safety of existing plant.

Evaluation against standard SWOG criteria

SWOG's evaluation of fission energy against its standard criteria is given in table A5 below. Among the technologies SWOG has considered in its first work programme, nuclear fission power is unique in its ability to generate economic power on a much larger scale than now, with fossil fuel prices not very different from current ones. However, it is also unique in that the nuclear industry is largely convinced that safety and waste management concerns are unfounded although it cannot, so far, convince the public of this.

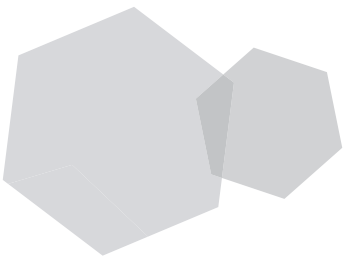
Table A5: Nuclear fission against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	good - roughly competitive with gas and coal without CO ₂ penalties excellent excellent
Health and Safety Impacts to work force to public	very good very good - for new plant
Environment Friendliness locally global warming	very good - but proof is difficult excellent
Input Sustainability	good - with current reactors, very good - with breeder reactors
Security of supply	excellent - easy to store fuel
Compatibility with EU needs	excellent - for base load
Deliverability	excellent - can store waste above ground for time being
The need for EU-wide R&D	excellent - need collective evaluation of designs and demonstrations
Secondary (spin-off) merits	Poor
Special Factors	very difficult - strong public antipathy; proliferation, safety and waste worries

Sources of information and data

Acceptable Nuclear, by Alain Gerard, AGE SWOG 2003-4-28

Nuclear Energy, by Kaija Kainurinne, AGE SWOG 2003-4-31.



Annex 6: Nuclear Fusion

Background

The fusion of light nuclei into heavier ones releases energy. The sun and other stars are powered by fusion and, in that sense, many renewable energy sources (direct solar, wind, waves, biomass) are fusion energy at source.

In 1937, Rutherford predicted a fusion reaction between the two heavy isotopes of hydrogen, deuterium and tritium. This highly exothermic reaction occurs in a sufficiently hot DT plasma (ion temperatures of 10^4 eV or 100 million °K are necessary; hence the phrase thermonuclear fusion) and has been at the heart of all fusion R&D, both for electric power production and for 'hydrogen' bombs. Other fusion reactions, such as between two deuterons, or D and He³, or those involving heavier elements taking place in the sun and stars, are also possible but need even higher temperatures and are therefore more difficult to achieve than DT fusion.

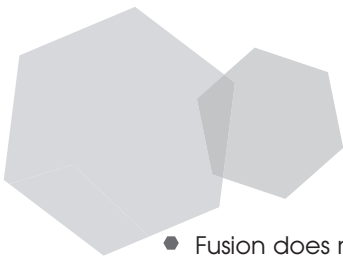
The confinement of deuterium and tritium at such high temperatures in a material container is out of the question, and two very different approaches have therefore been followed. One aims for lengthy magnetic confinement of a very hot but relatively low-density plasma for electricity production; the other for the so-called 'inertial confinement' of a much denser plasma for a very short time, central to nuclear weapons but not entirely out of the question for power production either.

France and the UK, the EU's two nuclear-weapon states, and the USA have programmes on the use of lasers in fusion (thought to be central to controlled inertial confinement) but the EU-coordinated fusion energy R&D programme concentrates almost entirely on magnetic confinement, currently thought to be the best bet for power production. EU and worldwide efforts to create, control and sustain a fusion reaction in this way have been ongoing since the 1950s and we are now very confident of its basic physical feasibility. However, many technical obstacles not originally foreseen have had to be overcome and, although there are now clear road maps for future development, we are still several decades from a full-scale fusion power station.

The potential advantages and the status of development

Nevertheless, the many attractive features of fusion energy, as compared with fossil fuels, nuclear fission and renewables, have ensured that the development efforts have continued worldwide. Its potential advantages are that:

- The lithium ores which provide the tritium for fusion are widespread, abundant, with few competing uses and are easy to stockpile. The deuterium is available in all ordinary water.
- Fusion is a concentrated energy source, with modest land use and minute material feedstock requirements. It would be easy to place fusion power stations where their visual impact was small, including on coasts to avoid the need for freshwater or cooling towers.
- Fusion is not linked to solar or lunar cycles, nor subject to the vagaries of the weather or seasonal climate, making it well-suited for baseload generation.



- Fusion does not produce greenhouse gases nor any of the air pollutants of combustion.
- It cannot experience a big nuclear accident, that is one releasing large quantities of radioactivity to the environment.
- Although it does generate radioactive isotopes, most are relatively short-lived. In particular, it does not produce actinides, the major contributors to very long-lived nuclear waste from fission reactors, and geological storage of fusion wastes would probably not be necessary.
- There are no obvious limits to the extent to which it can be used; it could conceivably provide all baseload electricity generation for the whole EU.
- Essentially, all the costs are in the technology, in which Europe could easily be self-sufficient.

A disadvantage of fusion power is that each reactor will have to be very large, of the order of 1GW compared with 1MW for a wind generator, thereby increasing the financial risks in each construction project and limiting the rate of progress along the learning curve. Large sizes are needed because the ratio between energy production in the burning plasma (proportional to its volume) and energy loss at its surface (proportional to its surface area) must be large enough to allow the required high plasma temperatures to be maintained. This large module size also makes fusion development slow and extremely expensive and will probably limit its application, even if successful, to supplying electricity to large urban areas in highly industrialised economies like the EU.

The uncertainties which remain about its potential for practical electricity generation are no longer primarily about whether burning deuterium/tritium plasmas can be confined and controlled with magnetic fields, and kept sufficiently dense and hot. Experiments in JET (EU) and TFTR (USA) in the 1990s demonstrated that beyond reasonable doubt, although not yet with full 100% certainty. Thus, the EU's work with JET has demonstrated that:

- Sufficiently large values of the crucial 'triple-product' (the product of plasma density, temperature and confinement time) for a self-sustaining burn in a hydrogen plasma can be achieved in physically large devices. Forty years ago, achievable triple products were ten thousand times too small for a fusion reactor. Twenty years ago, before JET, they were 100 times too small. JET has taken them right up to the break-even region where as much fusion energy is produced as is needed to generate the plasma. This is now only a factor of five short of what is required for practical power production, a small gap if recent progress can be maintained.
- Each of the three components of the triple product can individually be taken into the region required for fusion reactors.
- Burning deuterium/tritium plasmas, producing significant fusion power, can be controlled for extended periods of time without suffering the instability events which dogged the earlier work.
- It is possible to operate fusion devices safely with radioactive tritium fuel and to maintain and modify radioactive structures using remote-handling techniques.

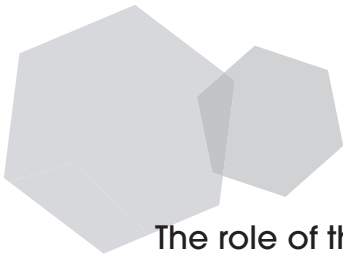
Carrying fusion development forward

It is still necessary to demonstrate conclusively that all the required plasma conditions can be achieved simultaneously and maintained for long periods of time. As a consequence, during the past ten years or so, the major focus of the fusion development programme has been on the design of ITER (International Thermonuclear Experimental Reactor), capable of sustained DT burn. If built and operated successfully by the international partners involved (the EU, Japan, USA, Russia, China and South Korea), ITER would demonstrate with certainty our ability to control and maintain burning plasmas for extended periods of time. ITER would also provide experience in the integrated operation of all the components of the technology: operation with super-conducting magnets, particle and power exhaust, working in a very radioactive environment with remote handling, tritium breeding, etc. SWOG agrees that ITER should be built as soon as possible, preferably in Europe, to demonstrate fusion's technical feasibility with certainty and to gain some experience with the operation of realistic-scale fusion technology and sub-systems. The project should be carried out as an international collaboration to share the costs, but with the EU playing an active leading role.

However, success with ITER will still leave major technological and engineering hurdles along the path to a demonstration reactor and a full-scale, fusion power plant. These would be in how to construct and maintain the many, very high-tech components which are at the heart of fusion reactors. Thus, fusion reactors will need a very high-temperature first wall, with key components exposed to hot hydrogen plasmas, very low-temperature superconducting magnets with large quantities of stored energy, a very high-vacuum torus, high-temperature liquid metal or salt-cooling circuits; and complex energy and material injection and extraction equipment. All will be heavily neutron-irradiated during normal operation, may be seriously damaged at any time by a major plasma disruption, yet will have to be built and maintained at sufficiently low costs and achieve high-enough availabilities to allow economical electricity to be produced.

SWOG believes these are now the major uncertainties over fusion technology as a practical energy source and need to be tackled in parallel with ITER to avoid an unreasonable delay in finding out how useful fusion will be in meeting future energy demands. SWOG believes, therefore, that the global fusion community needs to build a device such as the IFMIF (International Fusion Materials Irradiation Facility) to test fusion reactor materials and components before they are incorporated in a reactor, and to develop a systematic understanding of how materials degrade when irradiated by 14Mev neutrons, since this will be crucial to determining the practicality of fusion and cannot be tested on ITER.

Conventional tokamaks, like JET and ITER, are the best-developed fusion energy systems but it is possible that alternative concepts, such as the so-called 'spherical tokamak' or the 'stellarator', might be better. SWOG therefore recommends that some EU effort on fusion is reserved for work with these until our experience with ITER demonstrates whether or not they are not needed. They also extend the database on which our knowledge of fusion reactors rests and should help to reduce the risks in building future plants. Also, although the construction of ITER and tackling materials issues for power-producing reactors should be given most of the EU's fusion RTD resources over the next decade, SWOG believes we do need to maintain some expertise in core plasma physics. This will be necessary to deal with any problems or surprises in ITER or with the alternative concepts, and may provide the key to devices with lower costs and better performance.



The role of the European Research Area

We have already noted that fusion reactors will inevitably be large-scale and expensive devices. As a consequence, major experimental facilities like JET and ITER are already too expensive for individual EU Member States and the R&D has properly (and very successfully) been carried out on an EU-wide basis, with expertise pooled and costs shared. Carrying out fusion R&D on a Europe-wide basis has also allowed the required high-tech expertise to be drawn from all Member States. SWOG believes that EU fusion research has effectively been an ERA for many years and must remain so.

Moreover, the EU-wide consensus on fusion has enabled the EU to play a leading and extremely important role in the global ITER project, providing consistent leadership in the face of US fickleness over ITER and always being ready to provide the site. SWOG believes it is therefore far better for EU members to participate in the global ITER project as the EU, whose influence will often be decisive, than as individual Member States each having only a modest influence.

Evaluation against standard SWOG criteria

SWOG's evaluation of fusion energy against its standard criteria is given in table A6 below. If the development of the technology is successful and energy prices rise substantially and/or large carbon taxes are introduced, then the use of fusion power stations will be very large, meeting the whole of EU demand for baseload electricity if necessary. The risks and uncertainties surrounding fusion energy remain substantial and the EU needs to tackle them quickly. Doing so will not only minimise overall fusion development costs but also clarify quickly whether fusion will or will not be a decisive energy contributor in the future, with the consequent major impact on energy R&D strategy.

Table A6: Fusion against evaluation criteria

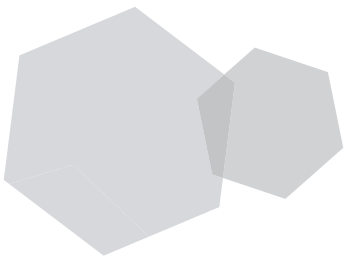
Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	nil possibly some possibly large in the long term
Health and Safety Impacts to work force to public	excellent excellent
Environment Friendliness locally global warming	excellent excellent
Input Sustainability	excellent
Security of supply	excellent
Compatibility with EU needs	good - though probably only for baseload operation
Deliverability	slow - since each plant will be large and complex
The need for EU-wide R&D	excellent - an ERA already in place and becoming global
Secondary (spin-off) merits	few
Special Factors	public attitude good

Sources of information and data

Practicable Nuclear Fusion, by William d'Haeseleer, AGE SWOG 2003-5-38a

Final Opinion of the EAG-FU (1998-2002), by William d'Haeseleer

Fusion, JET and the EU research programme, Jerome Pamela, AGE SWOG 2003-5-38b.



Annex 7: Solar Photovoltaics

Background

By far the most important energy source for all life on earth is the sun. Its energy is generated deep in its interior by nuclear fusion reactions, is carried to the surface we can see in the daytime sky by high-energy radiation and convection, and then to Earth and down through our atmosphere by sunlight, that is electromagnetic radiation primarily in the visible and infra-red. The sun also emits some ultraviolet light and high-energy particles, but the major fraction of the solar energy reaching the earth's surface is just visible and near-infra-red light. The energy content of the sunlight reaching the earth is some hundred thousand times bigger than mankind's total current energy use and solar photovoltaic (PV) technology simply aims to use some of this torrent of free energy to make electricity.

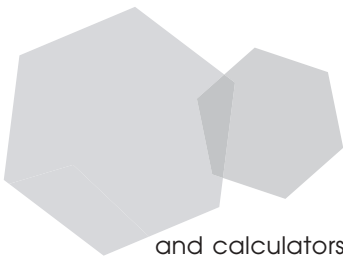
As far back as 1839, Becquerel demonstrated a link between light and electricity, but effective solar cells that could convert light into electricity only became possible after the development of semiconductor diodes and transistors in the 1930s and 1940s. In 1955, the US Bell Labs patented a solar cell based on silicon, creating what has proved to be the most important solar cell technology so far and enabling an understanding of their operation to be gained which has guided the development of cells based on other semiconductors such as gallium arsenide, cadmium telluride and copper-indium-diselenide.

The intensity of sunlight falling on the surface of the earth when the sun is directly overhead can reach 900 watts per square metre but the average intensity is usually in the range of 90 to 290 Wm^{-2} . Laboratory cell efficiencies can be up to 45%, but current commercial cells only reach 17% and the average system efficiency for terrestrial applications is only 10-13%. As a consequence, solar cells need to cover large areas if significant electrical powers are to be made. Fortunately, only a very thin layer of the often-expensive active material is needed for solar cells, but thin PV junctions covering large areas need good physical support which can itself be costly. Using the roofs and the façades of the buildings in which the electricity will be used as support for the cells in so-called building-integrated PV (BIPV) is consequently a favoured approach.

Individual solar cells make low-voltage direct-current electricity and most PV installations therefore need additional equipment to convert this to the medium-voltage alternating-current electricity that is easy to switch and transport and for which most modern electrical equipment is designed. Finally, PVs can only make electricity during daylight and, in most applications for bulk electricity, they must therefore be used in conjunction with storage devices or back-up sources. Stand-alone or 'hybrid' installations have their back-up sources or electricity storage co-located with the solar cells; grid-connected installations rely on normal electricity grids but require appropriate connection equipment. The solar cells themselves are therefore only part of what is required for practical PV electricity.

The potential

Nevertheless, PV systems have proved to have enormous advantages over conventional energy sources, such as diesel generators, in remote off-grid applications, such as communication repeaters in sunny countries, and in mobile specialist devices such as watches



and calculators. As a consequence, they have already created a successful global industry. Total installed capacity is now over 3GW worldwide. In 2004, PV module production stood at 700 MW and the market for PVs is expanding at 20-35% per year. Therefore, SWOG does not see any need for EU-wide support for PV cells and systems aimed specifically at the off-grid market, although manufacturers will doubtless continue to improve their cells and systems and should be encouraged in the usual ways, via tax relief on R&D, support for deployment in new markets, etc.

As sources of bulk electricity, connected to electricity grids, PVs meet most of SWOG's evaluation criteria with flying colours (see the table at the end of this annex). Their input energy is 'strictly' sustainable in SWOG terms; the raw materials needed for their manufacture are very widespread; they pose only modest safety risks to the workforce (during installation and cleaning) and none to the general public; they do not cause any noise or greenhouse or any other gaseous emissions when in use, although some types of cells would constitute toxic waste at the end of their lives; when used as roofs or façades for buildings they cause little visual intrusion; and they cannot be significantly disrupted by any political, economic or terrorist incidents. Their drawbacks are that they cannot easily meet electricity demand at night or in more northerly, more cloudy countries of the EU; their take-up is likely to be slow if it has to be linked with replacing or refurbishing buildings; but, above all, their costs are currently too high.

Even without electricity storage PVs have the technical potential to supply much of the daytime electricity needs of countries where the climate is usually sunny. Most of the southern Member States of the EU-25 fit this bill, with a total current daytime demand of about 800 TWhr, approaching a quarter of the total EU electricity demand. Moreover, since electricity demand in domestic and commercial buildings in sunny countries tends to peak in the daytime in sunny weather – because of equipment used during the working day and air-conditioning – some conventional capacity savings as well as large fuel savings can be made in this application. PVs would usually be installed on the buildings needing the energy, or fairly close by, so they would also lead to fewer losses in transmission.

With effective energy storage PVs could potentially meet more than just the daytime demand. Conversely, however, PV installations in more northerly countries without built-in storage do not allow savings in conventional generating capacity, since electricity demand here is often higher in hours of darkness or during periods of bad weather when PVs work less well. To give a simple first approximation therefore, a widespread economic contribution to EU electricity supply from PVs depends on achieving simple PV system costs which are low enough to compete with other energy sources on a fuel and transmission loss saving basis. This is a very tough target which PVs are still some way from meeting. It is particularly tough when the competition is baseload coal or nuclear plants where costs of the fuel to the power station owners are very low.

However, it is the case that, whilst PV installations are on a relatively small scale (and even the European Photovoltaic Industry Association expects only a 1% contribution to electricity supply by 2020), the costs of PV electricity need only be competitive with the retail price of power from electricity companies. This is a much softer target and is certainly helping PV electricity begin its penetration into the on-grid market. But if the ultimate impact of PV is to be large it will have to

meet the more difficult challenge of competing with more dependable bulk-power producers in the wholesale market where the costs of its inability to meet demand at night or in poor weather will have to be factored in.

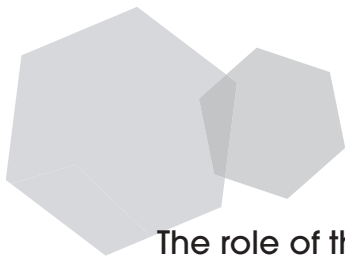
Achieving competitiveness

Current installed system costs for building-integrated PV in Europe are around 5-10 € per peak watt (PV module costs 3-6 € per peak watt). On a good site in southern Europe, with around 1 800 equivalent peak solar-power hours per year, assuming a capital charge rate of 6% and a system life of 20 years but no significant maintenance costs, this corresponds to an electricity cost of around 25-60 €cents per kWh. This is more than ten to 20 times the fuel and transmission costs of conventional electrical power with which PVs will ultimately have to compete if they are to make a large contribution to supply, but only one to eight times the retail price. There are two different approaches to making PVs more widely competitive, although they are not necessarily independent.

The first is to subsidise the deployment of the current technologies (the guaranteed price paid to solar generators in Germany is 46 €cents/kWh), and rely entirely on economies of scale and the learning curve of mass production. If enough solar cells are manufactured using the currently dominant silicon technology then the costs will be reduced – and silicon enthusiasts believe that these cost reductions will be big enough to ensure that these cells can eventually compete without subsidies. The second approach is to search for more efficient cells such as multi-layer junctions with a range of materials and/or more easily mass-produced technologies, such as amorphous silicon, and only to seek to make PVs competitive via installation subsidies when better technologies are available.

SWOG is not sure whether or not economic PV installations can be achieved with current silicon technologies, but it doubts it. They may compete with retail power on good sites but it is very doubtful that they can ever be truly economical against gas, coal or nuclear generation in large-scale use. Moreover, since the scale of PV production is already quite large, supplying as it does the existing off-grid and subsidised on-grid demand, the increased scale of production needed to drive the costs down to where they can truly compete will be enormous and the subsidies required to achieve those sales volumes will be very large too. However, since the subsidy strategy for making cells competitive may be used in some Member States, SWOG believes that some EU-wide research should focus on trying to optimise current PV systems via R&D on cheap 'solar-grade' silicon, crystalline silicon cell and wafer production technologies, balance of systems equipment, control systems for grid connection, safety and reliability issues.

But SWOG believes that the really important long-term R&D challenge is to find a PV technology concept which is significantly cheaper per unit output than crystalline silicon and lends itself more readily to mass production. There is as yet no clear winner among the various materials being studied such as amorphous silicon, copper-indium-diselenide, cadmium telluride, organic solar cells, etc., and fundamental R&D and new production technologies are required for all thin-film cells. SWOG therefore concludes that the main EU-wide R&D priority for PV should be on materials research linked with device physics and manufacturing technologies for promising thin-film and/or multi-layer PV technologies.



The role of the European Research Area

The problem of making PVs truly competitive in the bulk electricity market is an extremely difficult one and will not be solved quickly or perhaps not at all unless Europe's best researchers in the area are closely coordinated and can build on each other's advances. SWOG believes that the EU needs to have a major campaign to develop novel PV technologies which can attract our best researchers and our most innovative production engineers. The scale of the research may not initially be very large but the researchers need to work closely with industry to make sure new technologies take proper account of the opportunities and constraints in thin-film manufacturing.

Evaluation against standard SWOG criteria

SWOG's evaluation of solar photovoltaics against its standard criteria is given in table A7 below. The block of 'excellent' ratings in the centre of the table indicate why PVs are so highly thought of by the public and politicians. In the north of the EU, the problems of inherently low load factors and incompatibility with customer needs (in not delivering power during periods of darkness or bad weather) are probably insurmountable. In the south, the only real obstacle to the wider use of PVs is their cost.

Table A7: Solar photovoltaics against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	nil for the foreseeable future probably nil possibly large in the long term
Health and Safety Impacts to work force to public	excellent excellent
Environment Friendliness locally global warming	excellent excellent
Input Sustainability	excellent
Security of supply	excellent
Compatibility with EU needs	poor in the northern EU - because of diurnal, seasonal and weather variation good in the southern EU
Deliverability	very slow - if it has to be part of the building fabric
The need for EU-wide R&D	good - for the difficult search for better PV technologies
Secondary (spin-off) merits	excellent - major markets outside EU
Special Factors	excellent - strong public support

Sources of information and data

Affordable Solar Electricity: Photovoltaic Systems, by Gerhard Faninger, AGE SWOG 2003-4-33
Affordable Solar Electricity: Building on a Decade of Industrial and Political Commitment, by Murray Cameron, AGE SWOG-4-32
Renewables for Power Generation: Status and Prospects, OECD/IEA, 2003.

Annex 8: Wind Energy

Background

Atmospheric wind is created by sunlight, the energy of which is converted into the movement of air via convection in the atmosphere and evaporation over oceans. Wind energy is therefore fully renewable with very low external costs. Moreover, despite its use in Europe for many hundreds of years for grinding corn and pumping water, there is a large unrealised potential for wind power generation in the EU.

Life-cycle analyses show that modern wind generators have an energy payback time of about three months – for average sites in Denmark. Since the design lifetime for these wind turbines is 20 years, over their lifetime they will produce around 80 times the energy it takes to make them. The analyses also show that practically all the materials used can be recycled – there are no long-term wastes.

The EU has attained a leading position in electricity generation from wind power. Thus, 75% of worldwide wind energy capacity is installed in Europe, primarily in Denmark, Germany and Spain. By 2003, there was about 29 GW of installed capacity in the EU, with some 5.5 GW of new capacity being added in 2003. It supplied over 60 TWhr of electricity in that year, the equivalent of about 1.7 times the Danish consumption, and 2% of overall EU-25 consumption. In Denmark and Schleswig-Holstein, more than 20% of electricity demand is now covered by wind turbines.

The majority of wind generators in Europe are connected to the electricity grid. They are mostly three-bladed, horizontal-axis turbines mounted on tubular or lattice towers, with rated powers of 600 kW upwards, rotor diameters and tower heights from 40 metres. The largest wind turbines currently being deployed have nominal powers of 3-4 MW with rotor diameters and tower heights of 80 metres or more, but even larger ones under development have nominal powers of 4.5 MW, rotor diameters between 110 and 120 metres and tower heights of more than 100 metres.

European wind energy resources are unevenly distributed geographically. Good wind sites are those where wind turbines can generate more than 3 000 full-load-equivalent hours of energy production per year; poor sites are those where they would reach less than 1 500 full-load-equivalent hours per year. In Denmark, the range of generation at different sites is between 1 800 and 3 000 equivalent hours for onshore sites, with an average around 2 200-2 300. Offshore sites are expected to provide between 3 000 and 4 200 equivalent full-load hours generation per year.

Next to conventional hydropower and biomass combustion, wind energy is economically the most competitive of the renewable energy sources. On a 3 000 hours equivalent full-load site, allowing €50/tonne for the external cost of CO₂ reduction in competing fossil plants and not charging any cost for standby power plant, wind is currently (early 2004) competitive with new coal, oil and open-cycle gas turbine power plants, but not with combined-cycle gas or nuclear power plants. Clearly, for the industry to stand alone without subsidies some further cost reductions are necessary.



The potential

The potential for the increased use of wind energy is huge. The report, "Wind Force 12", makes estimates of wind energy's technical potential in Europe and worldwide by calculating areas with an annual average wind speed exceeding 5 metres per second at a height of 10m. The estimated potential in Europe is about 4 800 TWh per year and worldwide some 53 000 TWh per year. The potential in Europe, which is offshore but less than 30 km from land and in water less than 30 m deep, is 630 TWh per year.

Naturally, the exploitable potential is rather less. Experience in Denmark and Germany suggests that it is feasible to utilise about 10% of the technical potential. Using this assumption, the European Wind Energy Association sets up a scenario for deployment in which wind turbines in Europe (EU-15) in 2020 produce 425 TWh annually – some 12% of the expected electricity consumption in Europe (EU-15) at that time. In "Wind Force 12" the EWEA suggests that wind power is capable of supplying 12% of the world's electricity demand in 2020, even if the overall demand increases until then by two-thirds. Whether such scenarios will become commercially attractive depends on whether or not wind power can be made competitive with the cheapest alternative including cost of back-up and external costs.

SWOG agrees that supplying 10 or more of Europe's electricity consumption from wind energy will offer major benefits but also present serious challenges. On the positive side, wind turbines will increase the indigenous provision of energy in the EU and should increase the overall security of electricity supply. The failure of one or more wind turbines would not affect the overall grid system the way the drop-out of a large conventional power plant may affect it. On the other hand, there will have to be a combination of novel and effective usage of dynamic grid-management, demand-management, energy storage and back-up capacity to deal with situations of no wind whilst electricity consumption is high.

There are also challenges to be faced in using wind turbines in different types of terrain. In Denmark and Germany, most of the current turbines and the potential new sites are on flat land or offshore in shallow water. In southern parts of Europe (Spain, Italy and Greece), the majority of turbines and the potential sites are in complex terrain. Three-bladed, upwind wind turbines sited on flat land have a long track record and good reliability. However, research is much needed concerning wind over complex terrain, aerodynamics, aero-elastics, structural design and materials, control, sensor technology, and grid integration and dynamics.

Offshore wind sites will place heavy demands on turbines to cope with the demanding environment (e.g. waves, ice, complex wind structure over rough seas) whilst achieving better reliability to avoid expensive service and maintenance visits. R&D is needed on new codes to calculate and verify the loads and strength (e. g. blades, gearboxes, etc.), new standards, and new materials for the multi-megawatt turbines.

Keeping the EU competitive in wind energy

Demand for wind turbines is almost certain to grow even further, not just in the EU but globally, and competition between the manufacturers supplying it will become intense. SWOG believes that the competitiveness of EU companies in this global market will be crucially dependent on

their having access to relevant R&D derived from medium- and long-term research programmes, to provide ideas for revolutionary new designs as well as incremental improvements to existing designs.

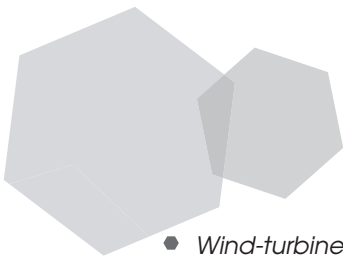
Thus modern wind turbines are pushing technology to extremes in several fields and needs research in areas such as meteorology (wind resources and wind structure), aerodynamics and aero-elastics, structural design and materials (composite materials, gear boxes, generators) and electricity grid modelling with fluctuating sources in the grid. Other industries should also benefit from this frontier research.

Unfortunately, manufacturers often – but quite naturally – focus on short-term innovation and do not pay much attention to long-term perspectives. Moreover, the days are over when the fledgling European wind energy industry could depend on wind R&D being performed in national laboratories. Their future success therefore relies on the existence in the EU of the necessary research, available to EU companies at costs not too excessive compared with that currently supporting their US and Japanese competitors.

SWOG concludes that EU-wide support is needed to create open knowledge networks among the European research institutes and companies dealing with long-term generic and more fundamental R&D activities. A European Research Area in wind energy, which can support the sector through long-term generic and scientific R&D, should be the ambition, a necessary basic element of which will be the establishment in FP7 of an EU research programme dedicated to wind energy with the aim of supporting R&D projects and facilitating the development of a European Research Area in the wind energy sector.

To meet the challenges that face the European wind energy, the following R&D issues must be dealt with:

- *Wind resources (identification and characterisation of sites for wind-power parks):* Improvement of databases and models for complex terrains, as well as over the sea, is much needed.
- *Prediction of power outputs:* Reliability of short-term (6-48 hour) forecasts of power outputs is one of the most pressing issues in connection with management of wind energy and its integration into the electrical grid. This is a priority that requires EU and international co-operative efforts.
- *Offshore:* Offshore wind energy demands knowledge of ocean-atmosphere interactions with structures. There is a need for an R&D programme encompassing modelling and predictions of ocean currents and wave-state, wave-structure interaction (internal waves and surface waves), sediment transport, and ice conditions.



- *Wind-turbine technology (development of new, fourth-generation turbines):* In order to be economically feasible, offshore wind turbines must be large, reliable and easy to maintain, characteristics which are desirable but not quite so crucial for wind turbines ashore. The scale-up to multi-MW sizes requires turbine blades that are so big and have such complicated and huge loads that no one yet knows how to make them. Novel rotor concepts with aero-elastic wings utilising interactive, adaptive shape control of aerodynamic forces could reduce loads and strains and thereby weight and cost. This development will require research into 'intelligent' materials and extending computational fluid mechanics to include aero-elastic interactions between rotor blades and turbulent flows. More efficient generators and converters, e.g. directly driven generators, could open up new possibilities for making more efficient and lighter wind turbines. By adding classical power-plant characteristics to individual wind turbines, it may be possible to reduce the problems and costs associated with transmission systems. Vice versa, designing the grid in such a way that it can accommodate fluctuating wind energy is another possibility.
- *Grid integration:* The integration of wind energy into national grids requires on-line grid-security assessments, short-term reserve management, 'ride-through-default' capabilities to provide grid robustness of operation, remodelling of Europe-wide grid systems, etc. These radically different and better systems and techniques for dynamic grid management must be based on vastly improved systems integration (improvement of short-term forecasting of power outputs), systems analysis (economics, barriers, strategies for implementation), and better control technologies.
- *Stand-alone and hybrid systems:* System integration of wind generators with other power sources, such as photovoltaic solar cells (PV) or diesel generating systems, is essential in small grids where high reliability is required.
- *Environmental impact:* Conflicting goals for the use of the countryside by different interest groups are becoming more pronounced. Understanding noise generation and transmission is essential. Better design methods for noise reduction must be developed. Wildlife must be considered in the deployment process. This requires better background data and understanding of the behaviour of different species. This holds for both land and offshore applications. Turbine interference with telecommunications/radars needs to be studied and quantified.
- *Testing, standardisation and certification:* To support the technological development and to make market penetration easier, there is a need for further testing, standardisation and certification. The EU should support the research necessary for the certification of site assessments, design of offshore wind farms, design of wind farms in complex terrain, and the identification and quantification of uncertainties.

Evaluation against standard SWOG criteria

SWOG's evaluation of wind energy against its standard criteria is given in table A8 below:

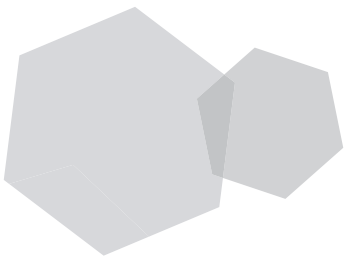
Table A8: Wind energy against evaluation criteria

Criterion	Comments
Potential Economic Contribution at current energy prices at 2 times current at 4 times current	some - can compete with coal and oil if CO ₂ is taxed and back-up is not required large - will compete with new fossil plant charged for CO ₂ even with back-up very large
Health and Safety Impacts to work force to public	excellent - installation and maintenance regulated by directives and standards excellent
Environment Friendliness locally global warming	good - but local concerns about visual intrusion and noise excellent
Input Sustainability	excellent
Security of supply	excellent
Compatibility with EU needs	fair - fluctuating wind requires back-up or demand management
Deliverability	excellent - modular units can be installed to match demand
The need for EU-wide R&D	good - need to maintain competitiveness of EU manufacturers
Secondary (spin-off) merits	good - export opportunities but US and Japanese competition
Special Factors	good - strong public support generally but some 'NIMBY' problems

Sources of information and data

Wind Energy, by Niels Busch, AGE SWOG 2003-6-40a

Wind Force 12, EWEA R&D Strategy, January 2004, Brussels.



European Commission

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