renewables 2004

Internationale Konferenz
für Erneuerbare Energien, Bonn
International Conference
for Renewable Energies, Bonn

Research and Development

The Basis for Wide-spread Employment of Renewable Energies

Thematic Background Paper

December 2003

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Editing: **Secretariat of the International Conference for Renewable Energies, Bonn 2004**

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This is one of 12 Thematic Background Papers (TBP) that have been prepared as thematic background for the International Conference for Renewable Energies, Bonn 2004 (renewables 2004). A list of all papers can be found at the end of this document.

Internationally recognised experts have prepared all TBPs. Many people have commented on earlier versions of this document. However, the responsibility for the content remains with the authors.

Each TBP focusses on a different aspect of renewable energy and presents policy implications and recommendations. The purpose of the TBP is twofold, first to provide a substantive basis for discussions on the Conference Issue Paper (CIP) and, second, to provide some empirical facts and background information for the interested public. In building on the existing wealth of political debate and academic discourse, they point to different options and open questions on how to solve the most important problems in the field of renewable energies.

All TBP are published in the conference documents as inputs to the preparation process. They can also be found on the conference website at www.renewables2004.de.

Executive Summary

The wide-spread employment of renewable energies is a vital pre-requisite for the transformation of the global energy system towards sustainability. This evolutionary process can only be successful if intensified research and development (R&D) efforts provide suitable foundations. The current global trend of declining energy R&D expenditure does not meet the challenges of sustainability. Significant technological and non-technological R&D efforts must for example aim at the development of well-adapted dissemination strategies, the optimisation of existing conversion technologies, the exploration of novel potentials as well as the development of new supply structures and of more user-friendly applications. In this context, the paper provides a detailed overview of important technological and non-technological R&D issues for the future. It emphasizes especially the importance of a well-balanced long-term R&D strategy that does not neglect those renewable energy conversion technologies which are still expensive but have a quasi-unlimited sustainable potential. Some proposals for global R&D structures being pertinent to renewable energies are given.

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GRA comprises nine of the world's leading science and technology institutions: Battelle (USA), CSIR (South Africa), CSIR (India), CSIRO (Australia), DTI (Denmark), Fraunhofer-Gesellschaft (Germany), SIRIM (Malaysia), TNO (Netherlands), and VTT (Finland). It was created in 2003 to address global problems, especially in the key areas of water and sanitation, energy, health, transportation, and the digital divide.

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1. Introduction

Research and development is a pre-requisite for the evolution of global civilisations towards sustainable schemes. The development of the energy sector is especially relevant as it is inevitably linked to many aspects of sustainability, e.g. protection of the natural life-support systems, the eradication of energy poverty in developing countries and the prevention of geopolitical conflicts. This evolutionary process can to a certain extent already be based on successful R&D and industrial activities in many countries. However, in order to set up a global sustainable energy system, much more R&D is needed in a wide area of fields, for example:

- R&D on sustainable technologies for energy conversion, storage, transport and use
- R&D on economic, political and institutional schemes for the transformation of energy systems on all levels (local, regional, global)
- R&D on appropriate implementation of new energy technologies into societies
- R&D on methods of financing the evolution of the energy system on a global scale
- R&D on management structures to implement, organise and monitor the global transformation

The basis for R&D in these areas must be set up or reinforced globally. The chances and prospects of international collaboration and task sharing must be taken into account. Further, the significant time lag between the application-oriented basic research, the development of strategies and technologies and their market implementation must be considered in R&D strategies.
Apart from a renewable energy focus, many other aspects related to a sustainable evolution of the global energy system require strong R&D efforts: particularly energy efficiency in all sectors and on all levels, sustainable transport concepts, etc. It is important to realise that three major aspects are integral parts of the transformation strategy towards a sustainable energy system:

- renewable energies
- efficiency
- less carbon-intensive fossil energy conversion

It is argued that the subjects for non-technological R&D described below apply equally well to these 3 major aspects. The focus in this paper, however, will be on the R&D on renewable sources of energy. The other elements of a transformation strategy towards a sustainable energy system are, in most cases, beyond the scope of the renewables 2004 conference.

In the field of renewable energies, non-technological R&D comprises a wide variety of subjects (i.e. economic, sociological, political, etc.). For example, it is of major importance to develop well-adapted dissemination strategies in industrialised and developing countries. In this context, the effects of liberalisation and globalisation on the application of renewable energies should be further analysed. There is a strong need to develop strategies for enhanced capacity building, to perform studies on acceptance and on raising awareness. Stronger R&D on improved financing schemes and minimising overall costs is of utmost importance.

1.1 Sustainable potentials and long-term R&D

Following the direct equivalent method [Roehrl et al., 2000], the world's primary energy consumption was approximately 420×10^{18} Joule in the year 2000, of which 85% were covered by fossil fuels. In the context of increasing the share of renewable energies against the background of a rising overall energy demand, the potential of various renewable energies to contribute to a sustainable global energy supply is obviously of major importance. Frequently the related technical potential of renewable energies is much higher than the actual sustainable potential in which other aspects of sustainability are considered, e.g. land use for biomass energy. The German Advisory Council on Global Change (WBGU) has recently identified the sustainable potential of different renewable energy sources, e.g. 100 EJ/a for modern biomass use, 140 EJ/a for wind power, and 15 EJ/a in the long term for hydro energy [WBGU, 2003]. Only the sustainable potential of solar energy can be termed quasi-unlimited against the background of all projections of future human energy demand.

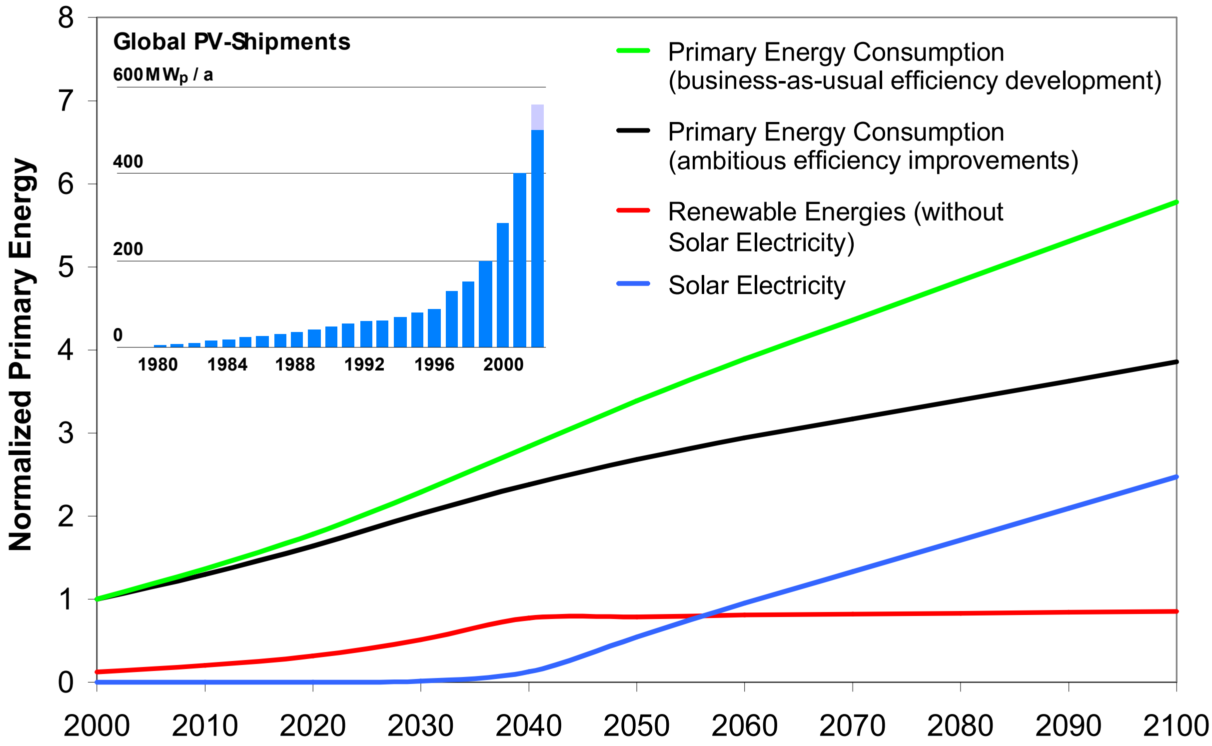
Renewable energies can be classified into two groups of energy sources:

1) already competitive, but limited overall potential (e.g. wind, water, biomass, PV for off-grid applications) and

2) still expensive, but quasi-unlimited overall potential (e.g. solar electricity by solar thermal power plants or PV).

The contributions to the global energy supply from the first group can be significantly increased over a short time period. Bulk solar electricity, however, will require a few decades to make large contributions on a global scale. It is absolutely essential to continue and enhance R&D work and efforts towards market introduction for all forms of renewable energy. Only the technologies with quasi-unlimited potential can cover the human energy demand in the long run (Fig. 1).

Figure 1: Global primary energy consumption in a fictitious high-demand scenario



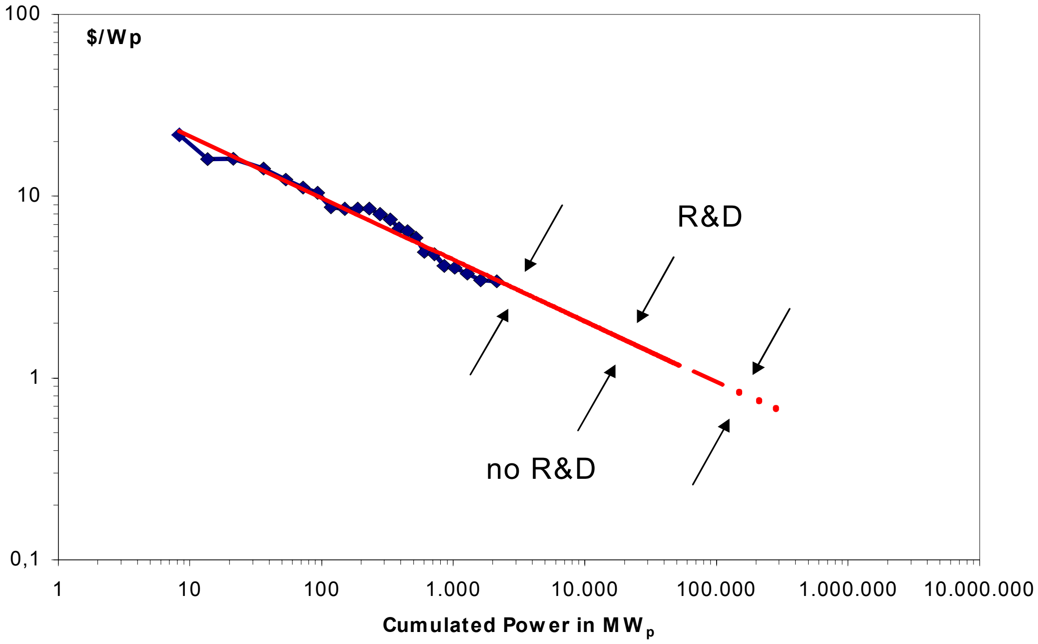
The red curve assumes high dissemination rates up to the maximum sustainable potential of the related sources, while the blue curve assumes a tenfold capacity increase per decade. All renewable energies together (= the sum of red and blue curve) are not expected to fully cover the primary energy consumption in the foreseeable future, so that the (decreasing) difference will have to be delivered by conventional sources. As a result, effiency improvements and less carbon-intensive fossil energy conversion are also of high importance. All given curves are normalised to the current global primary energy consumption. The figure underlines the long-term aspects of R&D in renewable energies and illustrates three major issues:

- Ambitious efficiency improvements have to be an integral part of a transition towards a sustainable energy system.
- An ambitious, but exclusive expansion of the mostly *already competitive renewable energy sources with limited overall potential* (i.e. wind, hydro, biomass etc.) is a necessary but not a sufficient condition for a future sustainable energy system as the limit of the related sustainable potentials might be reached rather soon. Only the further expansion of the nowadays *still expensive renewable energy sources with quasi-unlimited overall potential* (i.e. mainly solar electricity and probably solar H_2) can lead to a fully sustainable energy system in the long-term [WBGU, 2003].
- The blue curve represents a tenfold increase per decade of the solar electricity capacity from the very beginning of the century. However, even this ambitious development will lead to significant contributions to the global primary energy consumption not until the middle of the century. An exponential growth starting from a low level needs a long time to achieve high values and must be sustained continuously to meet the related targets. The inset shows the exponential growth of the global photovoltaics shipments.

1.2 General goals of R&D

In addition to mere energy conversion, it is vital to develop novel supply structures: distributed generation and grid optimisation, transregional energy transport and a global link, energy storage, load management, etc. It is also essential to improve the solutions for end-users: domestic co-generation of electricity, heat and cold based on renewable energy sources, biogenic bottled gas as decentralised energy carrier, and cars powered by fuel cells. In all these cases emphasis should be put on ecologically benign technologies (including recycling) and the cost effective generation, transport and utilisation of energy. In this context, continuous R&D efforts are essential for economies of scale as exemplarily shown in Fig. 2 for photovoltaics.

Figure 2: Exemplary price experience curve: photovoltaic modules (crystalline silicon)



So-called price experience curves (or "learning curves") are an established economic tool to express economies of scale and R&D-based technological improvements. They are based on the empirical observation of a constant percentage at which the unit cost generally decreases with every doubling of cumulative production. Learning curves can therefore be used to assess future price levels of a particular product.

Photovoltaics for example has shown a price reduction of approximately 20% with every doubling of the cumulative production over many years. This development must be sustained if a competitive price level is to be achieved in the future. The arrows given in the figure illustrate that, while enhanced R&D will contribute to reduce prices, a reduction of R&D will bend the price curve into the direction of slower price reductions. R&D is therefore an essential pre-requisite for competitive renewable energy prices in the future.

R&D should address today's technologies (upper left arrow), technologies at the horizon as well as "beyond the horizon" ideas of energy conversion.

Two main approaches must be followed. For one, new technologies have to be developed in some areas: biogenic bottled gas as decentralised sustainable energy carrier, low-cost energy efficient houses, additional storage schemes for high quality energy, etc. Secondly, cost reductions for existing renewable energy technologies have to materialise. The latter includes: higher efficiencies of energy conversion, longer technical lifetime of components, less maintenance, less material consumption, etc.

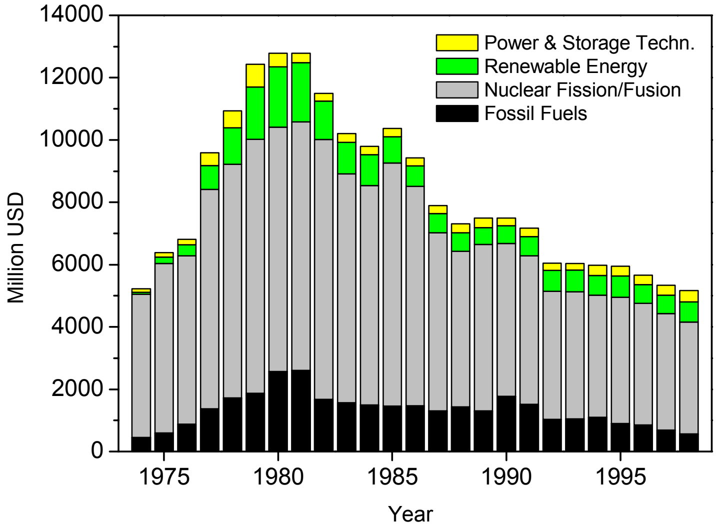
Parallel to this, R&D indirectly linked to the energy sector can foster the development of renewable energy technologies to a considerable extent. Developments in the fields of e.g. stand-alone electronic devices, off-grid telecommunication systems, and space applications may trigger additional developments and stimulate a synergetic market growth. Related applications may therefore increase the market volume of certain renewable technologies and thus help drive down the price experience curves.

2. State of affairs

Public global expenditure on R&D in the energy sector stems primarily from a small number of industrialised countries [WBGU, 2003]. For example in 1995, 98% of all IEA (International Energy Agency) member country energy R&D was carried out by only 10 countries [Margolis et al., 1999]. Figure 3 shows the public RD&D (Research, Development and Demonstration) budgets of 23 IEA-member countries for selected fields of energy-related research. About 70% of the expenditure shown was contributed to nuclear fission and fusion. Only 10% was contributed to renewable energies. The overall energy R&D expenditure peaked in 1980.

Since then it has been continuously declining to less than half its maximum level. At the same time the private R&D expenditure declined significantly in many industrialised countries, with the energy sector showing a particularly low R&D intensity, i.e. R&D as a percentage of net sales. This is especially worrying since evidence shows that energy R&D expenditure and patents are highly correlated, i.e. investment and innovation are closely linked. It is obvious that the global trend in energy-related R&D is contrary to the increasing strategic importance of the energy sector's evolution.

Figure 3: Public RD&D Budgets of 23 IEA-member countries for selected fields of energy related research

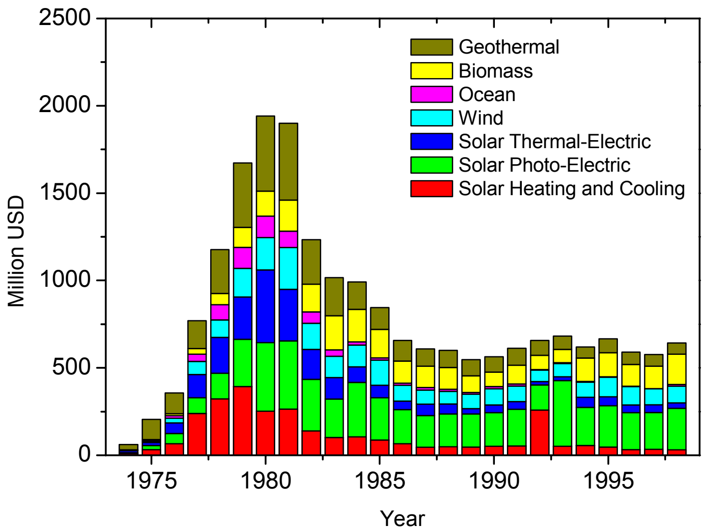


The figures illustrates the fact that about 70% of the related expenditure was contributed to nuclear fission and fusion, while only 10% was contributed to renewable energies. The overall energy R&D expenditure peaked in 1980 and has continuously been declining to less than half its maximum level since then.

Source: IEA Energy Technology R&D Statistics Service

Figure 4 shows the public RD&D budgets for renewable energy research in 23 IEA-member countries. Similar to the pattern shown in Figure 3 for overall energy expenditure, the expenditure on renewable energies peaked in 1980 and has since declined to about one third of its maximum level. Because less investment means less innovation, this trend is also in clear contrast to the ever-rising importance associated with renewable energies.

Figure 4: RD&D Budgets of 23 IEA-member countries for research on renewable energies



The figure illustrates that the RD&D-expenditure on renewable energies follows the trend in the overall RD&D expenditure on energy: It peaked in 1980 and has since declined to about one third of its maximum level. Two major developments may be identified when analysing the relative proportions of the different renewable energies within the overall Renewable Energy-RD&D budget: While biomass and photovoltaics show a trend to rising proportions, the other sectors remain on a constant or slightly decreasing relative level.

Source: IEA Energy Technology R&D Statistics Service

Various conclusions can be drawn from the above analysis concerning industrialised countries:

- R&D on energy technologies is concentrated in a small number of countries.
- The overall expenditure on energy R&D as well as the related expenditure on renewable energies peaked in 1980 and has significantly declined since then.
- The expenditure on nuclear technologies is many times higher than the expenditure on renewable energies.

Information on R&D activities in developing countries is quite limited and not available in an analysed format, but it is evident, as for the OECD countries, that only a small number of the larger countries have real R&D programmes on renewable energy technologies. Countries like China, India, Brazil, South Africa, Egypt and a few other countries do have major programmes dedicated to related R&D with significant developments. There are only very limited or no coordinated national programmes on R&D in most of the smaller and poorer countries although there have been some attempts at universities to create small scale programmes. However, these have often had too limited funding and laboratories become a random selection of donated equipment with little work associated. As already mentioned above, the energy sector is inevitably linked to many aspects of sustainability, e.g. protection of the natural life-support systems, the eradication of energy poverty in developing countries and the prevention of geopolitical conflicts. The above trends on R&D expenditure in both industrialised and developing countries are contrary to the related significance of R&D on renewable energies and therefore do not meet the challenges of sustainability.

3. R&D requirements

R&D measures must be adapted to the overall strategy for the evolution of energy systems. Certain technological solutions and non-technological approaches have to be ready for implementation at particular points of time (Fig. 1), whereupon a significant time lag between R&D and market launch must be considered. R&D on renewable energies is therefore a strategic field of research and industry policy which is inadequately steered and supported at present (Fig. 3 and 4). The following subsections provide an overview of important R&D aspects for the future. The list clearly has an exemplary character and cannot be complete. It shows the wide span of interrelated R&D challenges. There is no "golden way" based on just a small number of approaches, however, it is possible to define certain regional focal points.

- R&D on non-technological aspects (e.g. economic, sociological, political etc.)

- *R&D to develop proper sustainability indicators*
  The "sustainability level" of a certain development can be measured in part. It also depends, however, on background and cultural upbringing. There are no ideal independent indicators. Nevertheless a society needs guidelines to decide which development seems more attractive or less dangerous than others. R&D to determine realistic but flexible sustainability indicators is vital for proper policy choices.

- *R&D on the way innovation processes work*
  The way innovation processes work should be analysed in more detail regarding renewable energies. The best ways to stimulate innovation in the development of renewable energy systems should be found [Jacobsson et al., 2000]. Barriers to a speedy transformation of the energy sector should be identified and overcome.

- *R&D on world-wide price developments*
  More reliable price assessment techniques should be established for the technologies within the renewable energy sector. With these, better scenarios for R&D investments can be developed.

- *R&D on model projects*
  Five large-scale model demonstration projects have been proposed [WBGU, 2003] that would need intensive accompanying R&D especially in the areas of monitoring and analysis of such undertakings:

  - A strategic energy partnership between the European Union and North Africa, integrating into European power supply the potential of solar energy use in a manner profitable for both sides
  - Developing the infrastructure needed to substitute traditional biomass use by biogenic bottled gas
  - Low-cost energy-efficient buildings in developing countries

- Improving the power quality in weak electric grids in rural regions of developing countries via the integration of novel distributed power supply-technologies (renewable energies, storage systems, suitable power electronics etc.)
- "1 million huts electrification programme" for developing countries, generating the necessary internal dynamics for rural electrification

- *R&D on economic foundations*
  The world-wide economic foundations of energy system development schemes should be further analysed. Research on well-adapted dissemination strategies in industrialized and developing countries should be enhanced. Improved financing schemes for the effective evolution of today's energy system should be developed.

- *R&D on the best use of international instruments such as the Clean Development Mechanism (CDM) and Joint Implementation (JI)*
  CDM and JI should be further analysed with regard to promoting renewable energies in the countries involved. The lessons learned from past experiences should be shared. Options for improvement should be considered in the further development of the Kyoto Protocol.

- *R&D on external costs of fossil and nuclear energy supply systems*
  The external costs of fossil and nuclear energy supply systems should be analysed in more detail. Strategies to internalise external costs and thus levelling the playing field for renewable energies should be developed.

- *R&D on the effects of liberalisation and globalisation in the energy sector*

- *R&D on improved capacity building*

- *Best practice analyses*

- *R&D on acceptance and awareness raising*

- *R&D on data and statistics*
  Sound planning decisions require a reliable data background, e.g. resource assessments of renewable energies in developing countries; market penetration of renewable energy technologies.

- *R&D on the effects of the energy system on human health*
  R&D on energy-related health problems should be intensified. Related solutions based on renewable energy should be developed.

- *R&D on income-generating end-user energy services*
  Renewable energies have the potential to make income-generating end-user energy services available in currently non-electrified regions. Related research including regional analyses of well-suited options to cover the resulting energy demand should be enhanced.

- R&D on renewable energies for electricity production

- *wind energy*
  development of offshore potentials, adaptation of the existing onshore technology to the particular requirements of applications in developing countries and extreme climates, further cost reductions through improved technologies, better grid-integration and operation management

- *photovoltaics*
  cost reductions for silicon solar cells, thin film cells, cells for optical concentration, novel physical approaches, life cycle analyses and recycling, power stations, system technology, building integration

- *solar thermal power plants*
  plant automation, thermal energy storage, novel materials, direct evaporation and novel concentration concepts, solar towers: implementation of gas turbines, solar/fossil– and solar/biomass–hybrid systems,

- *hydro power*
  further improvement of micro-hydro technologies, advanced environmental risk assessments and full greenhouse gas accounting for dam projects

- *biomass energy*
  interface technologies to thermodynamic energy converters (e.g. co-generation plants, micro-gasturbines, Stirling-engines), integration of related systems into (micro-)grids, optimisation of the agricultural food-energy link, logistics, interface technologies to hydrogen technologies (syngas, fuel cells)

- *geothermal energy*
  exploration methods, stimulation techniques, efficient thermodynamic energy converters for low temperature-input, waste heat utilisation

- *maritime sources*
  technologies to exploit tidal and marine currents as well as wave energy

• R&D on renewable energies for the production of heating and cooling energy

- *solar water heating*
  long-term low temperature thermal storage, efficient collectors for process heat and sea water desalination, improved operation management
- *solar cooking*
  thermal storage, acceptance

- *solar cooling*
  development of electric/thermal hybrid systems, materials science (e.g. sorbents), system technology

- *biomass energy*
  adaptation of conventional heating plants to biomass based fuels, combustion with reduced emissions and less corrosion

- *geothermal energy*
  improved thermally driven heat pumps, seasonal storage, exploration methods, stimulation techniques

• R&D on solar and energy optimised buildings for domestic and non-domestic use (incl. solar heating and cooling)

- *solar optimised windows*
  improved heat insulation at high solar transmission, switchable glazings, daylighting concepts (e.g. microstructures)

- *wall insulation*
  active solar opaque facade for heat storage, vacuum insulation

- *heat/cold storage*
  micro-encapsulated phase change materials as wall coatings, air-to-ground heat exchangers, nocturnal ventilation concepts

- *novel HVAC (Heating, Ventilation, Air Condition) concepts*
  compact ventilation and heating units, solar thermal cooling, heat pumps

• R&D on renewable energies for fuel production

- *biogenic fuels*
  feedstock suitability, cost reductions for mature technologies (e.g. biodiesel), production of syngas and synthetic fuels, gas purification for fuel cells

- *hydrogen from various renewable sources*
  advanced electrolysis, utilisation of solar thermal energy in methane reforming, direct water splitting

- *solar chemistry*
  photochemical synthesis of energy carriers, photobiological and –chemical hydrogen production

• R&D on comprehensive technological aspects

- *distributed generation and grid optimisation*
  integration of fluctuating and decentralised energy sources into electricity grids, co-generation of heat/cold/electricity, advanced demand side management, power electronics, related information technology, demand forecasting

- *system technology for off-grid applications*
  advanced maintenance and diagnostics concepts, theft protection

- *transregional electricity and gas transport, global link*
  high-voltage direct-current transmission, high-temperature superconductors

- *heat storage*
  phase change materials, sorbents, long-term storage concepts

- *storage of high exergy energy*
  hydrogen technology, new electrochemical storages (batteries), storage based on superconductors

- *energy meteorology*
  spatially resolved prognosis of renewable energy potentials, local forecast of energy fluxes (e.g. wind speeds)

- *R&D on the sustainability effects of large scale application of renewable energies*
  possible recycling of wind turbine blades, minimisation or re-use of toxic materials in PV production, reduction of emissions during biomass conversion, reduction of energy payback times of renewable systems

- *R&D on standardisation of renewable energy products*

- *R&D on solar city planning*

Some of the above mentioned technologies are already in application; some are visible on the horizon. Technologies which are still beyond-the-horizon are broadly discussed in academia. It is important to identify a time-dependent, optimised mix of the different technologies and beyond-the-horizon-approaches [FVS, 2003].
Research requirements not only have to be well analysed in respect of time but also in respect of place. For some countries it might be advantageous to develop novel high-technologies (e.g. in photovoltaics), for others it might be beneficial to work primarily on the adaptation of existing technologies to local needs. Concepts that appear well-suited for a certain region might be inappropriate in other cultural or climatic environments. In addition, the acceptable costs of renewable energy applications vary widely between different regions. Country-tailored approaches are therefore an essential element of research planning.
It is important to perceive R&D and the application of its results in the energy system as a continuous interrelated process that leads to a sustainable energy system in the long-term. Particularly R&D strategies have to be reviewed and updated on a regular basis.

4. Policy implications and recommendations

Both non-technological and technological R&D on renewable energies are essential for the evolution of the energy sector towards sustainable schemes. It is a vital pre-requisite for the development of well-adapted dissemination strategies, schemes for enhanced capacity building and for raising awareness, price reductions, the optimisation of existing conversion technologies, the exploration of novel potentials as well as the development of new supply structures and of more user-friendly applications. Against this background it is highly paradox that the R&D-expenditure on renewable energies peaked in 1980 and thereafter has declined to about one third of its maximum level. In order to reverse this trend, it is recommended to increase at least ten-fold the average direct state expenditure for R&D in the renewable energy sector in industrialised countries until 2020. At the same time, significant international support must also be directed to R&D in developing countries.

4.1 R&D structures and institutions

In order to reach the ambitious targets, educational and scientific institutions must adapt to meet the challenges. Synergies should be created, parallel work avoided. Networks of universities and even virtual R&D institutions could serve as powerful and efficient elements of future structures. In this context, R&D on renewable energies should be integrated into existing R&D structures in order to use mutually advantageous conjunctions (e.g. in the areas of material sciences and nanotechnologies). Partnerships should be based on a win-win philosophy. The issue of intellectual property rights on technologies has to be addressed. Particular support should be given to R&D co-operation between developing countries. Perhaps initial catalytic support could come from well-established R&D institutions, for example, involving technology transfer and capacity building.

R&D on renewable energies can be improved at international academic institutions in a variety of ways:

- Related curricula could be fostered and co-ordinated internationally (see below: WERCP).
- Academic degrees that are approved internationally should be established.
- Exchange programmes for scientists and lecturers should be intensified.
- Stimulating rewards should be created for outstanding young scientists and lecturers.
- New research groups should be founded particularly in places with little activity at present.
- Materials sciences should receive distinctive support as they lay foundations for novel technological solutions in a wide range of fields.
- Appropriate internet discussion forums for scientists should be established on renewable energy–R&D related subjects.
- Information campaigns aiming at decision-makers and the general public should be mounted in order to raise awareness concerning the importance of R&D on renewable energies.

In order to foster and co-ordinate global R&D in an optimal way the following issues should be addressed at central institutions on a global basis, e.g. within the UN:

- *analysis and evaluation* of the global energy system with an emphasis on sustainability, identification of options for actions and R&D

- global and regional *consulting and co-ordination of R&D*, especially in scientific and technological areas of paramount importance

- *financing* of R&D activities and related institutions in order to realise the global development and implementation of renewable energy technologies with due velocity

These issues are detailed in the following:

Analysis and Evaluation:

It is important that the political implementation of a sustainable energy system receives continuous support through independent scientific input. This is currently the case in climate protection policy through the IPCC. Thus, an Intergovernmental Panel on Sustainable Energy (IPSE) charged with analysing and evaluating global energy trends and identifying options for action and R&D should be established [WBGU, 2003].

Consulting and co-ordination:

A "World Energy Research Co-ordination Programme (WERCP)" [WBGU, 2003] could be established perhaps within the UN system. Here, the various strands of national-level energy research activities could be drawn together in analogy to the World Climate Research Programme. Shortcomings could be identified, novel approaches evaluated, advise to local and regional scientific organisations be given, scientists exchange programmes organised, etc. Task sharing should be stimulated, i.e. global research strategies could be broken down into country-tailored national activities that meet the local demands (development of novel technologies, adaptation of existing technologies etc). The overall focus of WERCP should be on consulting and co-ordinating.

Financing:

International financing organisations (e.g. World Bank, Global Environment Facility) currently focus on the implementation of renewable energies but not on related R&D. This is a particular problem for countries with smaller R&D capability that want to perform e.g. research on the adaptation of existing technologies to local needs. A strategic global fund for R&D on renewable energies should therefore be established. The fund could be managed by the WERCP. In order to mobilise financial resources for the fund, innovative approaches should be taken into consideration. Apart from potential mechanisms related to the further development of the Kyoto-Protocol, raising charges for the use of global common goods, such as international airspace, deserves examination.

Last but not least, it should not be forgotten that strong R&D is carried out in industry. If government policy ensures proper markets (such as is currently the case for PV and wind power in several countries) then industries see the market potential and perform their own production-oriented research, complementing public research institutions. A proper balance has to be found between publicly sponsored R&D and industry financed R&D. This can be done through forming R&D consortia, where industry, R&D institutions and government work closely together.

4.2 Key issues in R&D

An exemplary list of R&D requirements has already been given in the related section of this paper. The following paragraphs summarise the main issues.

Recommendations concerning non-technological R&D

Identifying the individual and institutional barriers which hinder the wide-spread use of renewable energies is a vital pre-requisite for the future development of the energy system. Strategies to overcome the identified barriers should be developed. Further R&D aiming at well-adapted dissemination strategies in industrialised and developing countries is necessary. At the same time, research on the external costs of fossil and nuclear energy conversion should intensified and strategies to internalise these costs should be developed. The following points are also of primary importance:

- national market development strategies
- development of strategies for enhanced capacity building, awareness raising and information on renewable energies and their benefits
- research on optimum financing instruments that are well-adapted to regional characteristics (e.g. feed-in laws and quota-/certificate-schemes for grid-connected renewable energies, fee-for-service schemes and microcredits for off-grid electricity generation)
- research on the Clean Development Mechanism (CDM) and Joint Implementation (JI) in the context of renewable energy promotion

Recommendations concerning technological R&D

A large number of technologies can and must contribute to the evolution of a sustainable energy system. There is no "golden way" based on just a small number of approaches. R&D should cover the whole range of approaches listed under "R&D Requirements". A medium-term focus, however, should be given to:

- technologies that can be applied world-wide today in a cost-effective manner (e.g. solar and energy-efficient buildings, photovoltaic electricity for off-grid applications, biomass technologies),
- technologies that need only minor development steps in order to enter into completely new and large markets (e.g. solar thermal power stations and wind energy in developing countries, biomass-based synfuel),
- technologies that are absolutely essential for the long-term development

5. Acknowledgements

The final harmonisation of the paper was done by the energy executive board of the Global Research Alliance (GRA).

The following scientists and institutions have delivered further contributions to this thematic background paper:

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