R & D of Energy Technologies

toward future provision

／ electric energy
of - fuels in transportation sector
＼ high and low temperature heat

in sufficient amounts
environmentally safe
at sufficient low cost

by making best use

／ fossil ＼
／ nuclear fission ＼
of energy
＼ renewable ／
＼ nuclear fusion ／

edited by

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Contents:

Preface

The general assembly of IUPAP at Berlin in October 2002 formed a Working Group on Energy, to which it gave the task to provide

a survey of R & D of Energy Technologies toward the future provision of any kind of secondary energy demanded

- electric energy
- fuels in transportation sector
- high and low temperature heat

all in sufficient amounts,
environmentally safe
and at sufficient low cost

by making best use
of any kind of primary energy including

- fossil fuels
- nuclear fission energy
- renewable energy
- nuclear fusion energy.

This survey of R & D of Energy Technologies should help to sharpen the interest

- of scientists, esp. of physicists, in universities, in research institutions, in industry to devote their further work to this challenging field of science
- of media people to inform the public with sufficient completeness on this subject of vital importance
- of policy makers on the attractive potential for future ample business opportunities in the field of energy technologies as well as in many other fields.

To produce this report

- we invited scientific experts of many countries to provide short surveys of many different energy technologies describing the present status as well as the future R & D required to further develop the corresponding technology for proper ample use in the future
- we further have collected reports on the special energy situation in different countries around the globe concerning
    - the present demand on energy

  - the possible future demand on energy together with ideas how this demand might be met

  - the availability of different kinds of primary energy to provide any kind of secondary energy demanded

  - the needs of further R & D of future energy technologies

- we ourselves have briefly summarized the manyfold energy technologies and the collected reports on the energy situation in different countries. Furthermore we have drawn conclusions on the further need of R & D of energy technologies towards future provision of energy in sufficient amount, environmentally safe and at sufficient low cost, keeping in mind that availability of energy is a limiting factor to further economic development especially in many fast developing countries around the globe.

We would like to thank the scientific experts for their most informative contribution on special energy technologies and Herve Nifenecker for his country report on the energy situation in France.

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Executive Summary

The world population of at present about 6 billion humans is expected to culminate with about 9 billion humans around mid of this century, this further increase mainly due to developing countries with fast rising populations and fast economic development as well like e.g. China, India and Brazil. In the same period the global Gross Domestic Product is expected to further rise by at least about a factor 2 to 3, an appreciable fraction of it by fast developing countries like mentioned. With hopefully further rising energy efficiency - like in the past - to be achieved in already industrialized countries as well as especially in developing countries the further increase of the global demand on energy may be limited to about a factor 1.5 to 2.

To achieve this required provision of energy calls for physics achievements in the future by proper R & D of energy technologies

- to further provide sufficient secondary energy (electric energy, fuels in transportation sector, high and low temperature heat) with hopefully further appreciable increase of the energy efficiency allowing the development necessary to improve the life of people around the globe, especially in countries with further strong population growth, e.g. China and India

- by proper use of available primary energy sources
  fossil fuels
  nuclear fission
  renewable energy
  nuclear fusion

  - in an environmentally safe way reducing, respectively avoiding risks of nuclear energy as well as reducing, limiting risks and dangers of climate change

  - adaptable to possible changing environmental conditions not to be foreseen now

  - and last but not least at sufficient low cost.

Presently the main source of commercial primary energy (on global average about 85 percent) are the fossil fuels, coal, crude oil and natural gas.

At the present status of energy technologies the future provision of energy from non fossil energy sources is more or less rather limited,

- either because of limited availability (e.g. hydro power)
- and/or because of relatively high investment cost (e.g. nuclear fission power)
- or because of high respectively very high investment cost and missing availability of energy storage (e.g. wind power and photovoltaics).

Therefore fossil fuels are expected to continue to be the dominant source of primary energy at least within the next decades despite the danger of climate change.

To reconcile both confronting necessities

- to provide sufficient energy
- and to reduce further emissions of carbon dioxide from burning of fossil fuels to limit climate change

requires strong efforts on both

- R & D on non fossil energy technologies

    - nuclear fission
    - renewable energy
    - nuclear fusion

  to gradually substitute the further use of fossil fuels within some to many decades

- R & D on clean fossil energy technologies
    - increasing the efficiency of power plants
    - including CO_2 sequestration and deposition

  to allow fossil fuels to still be the major source of primary energy within the next decades.

It is an important and exciting task of physics concerning R & D on energy technologies, to discover and prepare new ways based on brilliant ideas, making use of computational physics, nano sciences and nano technologies to provide any secondary energy demanded from any kind of primary energy.

A large variety of energy technologies can be tackled by challenging R & D covering nearly any branch of modern physics, never restricted to one branch alone, always basic physics and applied physics linked together inseparably.

Renewable Energy

Further R & D on “solar” electric energy via photovoltaics, PV, is pursued on well established paths as well as on completely new roads to achieve much higher efficiencies and this at much lower cost.

Intimately connected to solar electric energy via PV is the required storage of electric energy

- either directly in rechargeable batteries hoping to finally achieve much higher storage densities and this at much lower cost than at present

- or indirectly e.g. via producing and storing hydrogen to be later used in fuel cells to produce electric energy

A further option of solar electric energy is the solar thermal power plant - restricted to low latitude arid regions with high insolation - especially with possible cheap storage of high temperature heat to provide electric power continuously.

Major further R & D on wind power is concentrated on the development of wind rotor generator units with some MW max. electric power to be installed “offshore” in shallow ocean regions to extend the intervals of providing electric power from typically up to about 20 percent of availability in time - typical for on shore and inland wind rotor installations - to about 30 to 40 percent.

Concerning hydro power

- the technologies of high pressure reservoir and low pressure river power plants are well established
- the technology of tidal power plants is available in principle and has been investigated comprehensively. But its further realisation beyond the existing 240 MW tidal power plant at the Rance estuary in France has been barred mainly by the rather high expenses to be expected.
- the technologies of ocean wave and ocean current power conversion still require extensive R & D both for large power facilities to be installed in the open ocean as well as for small power facilities to be installed in shallow coastal areas.

To provide biofuel from biomass may be rather promising for countries with proper large areas of land suitable for agricultural energy crops at present like e.g. Brazil. On a global scale the bottle neck for providing a large fraction of the demand on liquid fuels for the transportation sector is the limited availability of sufficient areas for agricultural land to provide sufficient amounts of food for a world population, expected to rise from about 6 to at least about 9 billion humans.

Hydrogen and Fuel Cells

Hydrogen is a secondary energy carrier to possibly be provided from any type of primary energy respectively of secondary energy like electric energy or high temperature heat. For future provision of hydrogen by large amounts rather challenging R & D along different new ways is required and is partially already going on, e.g.

- photo electrolysis (by special PV cells)
- solar thermal
- photo chemical - catalytic
- photo biological - water splitting
- thermo chemical

As an alternative to the difficult handling of hydrogen R & D towards converting hydrogen directly at the location of its production via synthesis with CO_2 extracted from the atmosphere to a proper synfuel like e.g. methanol may finally lead to avoid the expensive infrastructure of a future hydrogen economy.

Low temperature fuel cells, especially Polymer Electrolyte Membrane Fuel Cells, PEMFC, and Direct Methanol Fuel Cells, DMFC, are regarded as forthcoming future technologies for mobile provision of electric power especially on board of fuel cell electric motor vehicles.

Further challenging, rather imaginative R & D is required to overcome the many difficulties at present, last not least to reduce the cost of fuel cells by up to 2 orders of magnitude to become competitive with present vehicle propulsion by internal combustion engines.

Fossil Energy

Challenging R & D is required to do the splits between

- limiting the further increase of the CO_2 content of the atmosphere
- and making innovative use of conventional and non conventional resources of fossil fuels

and especially to do the splits between

- increasing the efficiency of fossil fuel fired power plants
- and implementing innovative CO_2 sequestration and deposition.

Nuclear Fission Energy

R & D is aiming towards

- evolutionary improvements of nuclear power plants to be built in the near future by further decrease of the of the risk of a large accident of Light Water Reactors and by avoiding the risk of a large accident completely by making use of inherently safe High Temperature Reactors

- revolutionary improvements of nuclear power plants to become available after many decades, perhaps heading finally for nearly closed fuel cycles via breeding and reprocessing of fuel and for reducing the radioactive waste largely by transmutation to shorten the lifetime of radioactive waste, if these technologies can become economic.

Nuclear Fusion Energy

Further necessary R & D for at least some more decades towards finally a technically as well as economically acceptable solution of fusion power plants is pursued at present with rather different options of fusion technologies

- magnetic confinement of the fusion plasma via TOKAMAK (next step: ITER) and STELLARATOR magnet configurations
- inertial confinement of the fusion plasma via LASER generated x-rays, electric pulse generated x-rays and heavy ion beams

until hopefully at least one of these options or even a further option like e.g. muon catalytic fusion leads to an acceptable solution.

Conclusions - Outlook

To be kept in mind: Fossil fuels will continue to be the dominant source of primary energy at least within the next few decades. It will take some to many decades to improve the use of other sources of primary energy like e.g. nuclear fission and renewable energy to be able to play a much more important role to satisfy our demand on energy than nowadays. This is intimately linked to the ability to cut cost of providing energy from nuclear and especially from renewable energy appreciably, and - concerning the increased use of renewable energy with strongly intermittent availability - to find new ways to store energy, especially electric energy efficiently and cost effectively.

Nuclear fusion energy may become an option only in the far more distant future of many decades. Therefore R & D on clean fossil fuel technologies with highest possible efficiencies and including CO_2 sequestration and storage respectively use is of utmost importance.

1. Introduction

The development of early mankind since some million years was extremely slow leading to a rise of the world population to a few million humans at the end of the last glacial period about 13,000 years ago [BRO].

Since the onset of the present interglacial warm period mankind was able for the first time to settle down, to provide increasingly more food by agriculture and cattle breeding, this because of the warm climate with its unusual stability in average temperature. During the 13,000 years up till about 300 years ago, the world population rose from a few million to about 600 million humans.

With the onset of the industrialization, since 300 to 200 years ago, the world population rose extremely fast from 600 million to already more than 6,000 million humans at present.

The industrialisation has been made possible by outstanding achievements of technology and science, especially physics. For example

- steam engine by J. Watt (1769)
- electric generator and motor by W. v. Siemens (1866)
- coal fired powerplants including an extended electric grid by H. Stinnes (1898)
- ICE motor car by C. + B. Benz (1888)
  ... for everybody by H. Ford (1903)
- electric battery by A. Volta (1798)
- electromagnetism by J. C. Maxwell (1861)
- electric light bulb by T. Edison (1879)
- electro magnetic waves by H. Hertz (1887)
- electron by J. J. Thomson (1892)
- transistor by J. Bardeen, W. H. Brattain, W. Shockley (1948)
- fast rising provision of food:
  - artificial fertilizer by F. Haber (1909)
  - high yield corn and wheat by N. E. Borlaug (1960).

Many of these and many more achievements led to a multiplication of man power by artificial power making rapidly rising use of fossil fuels

- coal since about 1700
- crude oil since about 1900
- natural gas since about 1950

These have been the main sources of energy because of their ample and steady, non fluctuating availability and - last not least - their relatively low cost compared to availability and cost of renewable energy used so far.

Within the last 100 years the global annual demand on primary energy rose from about 1 billion t coal equivalent to about 14 billion ce at present, of which

78 percent is from fossil fuels
6 percent is from nuclear energy
6 percent is from commercial renewable energy
10 percent is from non commercial renewably energy.

Now a look into the future:

The further rising world population is expected to culminate with about 9,000 million humans around mid of this century. At present nearly 2/3 of the total demand on energy is by industrialized countries with about 1/4 of the world population. Since many more countries, especially those with already high and still fast rising populations like e.g. China, India and Brazil exhibit fast rising economic development, the future global demand on energy is expected to rise by at least 50 percent within the next several decades.

The further availability of fossil fuels is restricted at present rates of consumption

- conventional crude oil to about 4 more decades
- conventional natural gas to about 7 more decades
- conventional coal to a few hundred years.

Furthermore it is of utmost importance to address climate change caused by climate warming induced by the exuberant burning of fossil fuels [IPCC]:
The direct release of heat by burning fossil fuels - globally only less than 0.01 percent of global warming by sunlight - is negligible. Not negligible but highly dangerous is the increase of greenhouse warming due to the increase of the content of the atmosphere on carbon dioxide: when burning fossil fuels about half of the carbon dioxide released remains in the atmosphere for at least some hundred years. Since burning fossil fuels as the main source of energy required by mankind the carbon dioxide content of the atmosphere has been increased by about 1/3, from 0.28 permille of volume about 200 years ago to 0.37 permille at present. Mainly this rise has led to an additional greenhouse warming on global average by about 1 percent compared to insolation of light, which has already caused a rise of the temperature on global average by close to 1 degree Celsius.

With still further rising consumption of fossil fuels with unrestricted release of carbon dioxide during the next decades we have to expect a further rise of the temperature by some more degrees. This rise of temperature poses the risk of climate changes most dangerous to mankind and to nature in many to most regions around the globe:

For instance

- the unusual stability of the global mean temperature, allowing agriculture and cattle breeding to provide sufficient food for at present 6 billion humans, may suddenly change to a climate with rapid fluctuation of the mean temperature similar to that of the preceding interglacial warm period between 130,000 to 115,000 years ago.

- the north polar ice cap may melt at least partially, leading to at least a strong reduction of the intensity of the gulf current rather suddenly - which transfers enough heat mainly from the equatorial Caribbean region to western and northern Europe, to additionally heat these regions by several degrees Celsius. This would lead to a decrease of the average temperature in Europe by several degrees, significantly impacting agriculture and forestry.

- in case of a melting of the west antarctic ice shield - which has happened during the previous interglacial warm period at a temperature on global and long term average of only about one to few degrees above the present average temperature on earth - the sea level would rise by about 5 meters, flooding coastal areas where about 1/3 of the world population is living at present.

To fight global warming sufficiently the further rise of the average temperature has to be limited as much as still possible, certainly to less than a few more degrees. This calls for a strong reduction of the release of carbon dioxide from further burning of fossil fuels on global average to less than ½ of the release at present, to be achieved hopefully within the next few decades.

To achieve this goal calls for <u>physics achievements in the future</u> by proper R & D of energy technologies

- to further provide sufficient secondary energy (electric energy, fuels in transportation sector, high and low temperature heat) with hopefully further appreciable increase of the energy efficiency allowing the development necessary to improve the life of people around the globe, especially in countries with further strong population growth, e.g. China and India

- by proper use of available primary energy sources
fossil fuels
nuclear fission
renewable energy
nuclear fusion

  in an environmentally safe way reducing, respectively avoiding risks of nuclear energy as well as reducing, limiting risks and dangers of climate change,
adaptable to possible changing environmental conditions not to be foreseen now
and last but not least at sufficient low cost.

2. Conclusions on the energy situation from reports in different selected countries and from global projections (see table 1)

At present

the highly industrialized countries of today

- with about 1/4 of the world population
- produce about 4/5 of the global Gross Domestic Product
- with a relatively high energy efficiency (consuming about 1 to 3 kWh of primary energy to produce 1 US$ of GDP)
- consuming about 60 percent of the global input on (commercial) primary energy

the less industrialized, developing countries of today

- with about 3/4 of the world population
- produce about 1/5 of the global GDP
- this with a comparatively low energy efficiency (consuming about 3 to 10 kWh of primary energy to produce 1 US$ of GDP)
- consuming about 40 percent of the global input on (commercial) primary energy.

In the past a significant rise of the energy efficiency in many sectors, especially in

- power plants
- internal combustion engines in vehicles
- construction of buildings with high efficiency for room heating respectively climatization

mainly in the highly industrialized countries of today has helped to reduce the rising consumption of energy. This partial saving of energy - having led to a corresponding saving of financial resources - has at least partially led to a further increase of the GDP without a corresponding increase of the demand on energy.

Thus hopefully in the future a further possible significant increase of the energy efficiency in all sectors, this in the highly industrialized countries of today as well as especially in the developing countries of today with fast rising population and further economic development (see table 1), can help to reduce the further rise of the demand on energy appreciably.

In most countries the main source of commercial primary energy - on global average about 85 percent - are fossil fuels: coal, crude oil and natural gas. They are used at present

- in power plants to produce electricity (about 40 percent)
- for fuels in the transportation sector (about 24 percent)
- for manufacturing, industry, construction (about 22 percent)
- for room heating (about 14 percent).

TABLE 1: ENERGY SITUATION

	Other Renew.	Hydro	Nuclear	Fossil	**Total PE**
YEAR 2000	0.25	0.25	0.7	8	**9.2** Bill. t OE

Industrial. Countries of Today	**1.5**	1 US$/ 1 to 3 kWh	4/5	60 %
Develop. Countries of Today	**4.5**	1 US$/ 3 to 10 kWh	1/5	40 %
World	**6**	1 US$/ 2.6 kWh	42,000 Bill. US$	100 %
	Popul. Bill.	**GDP/PE**	**GDP**	**PE**
World	**9**	1 US$/ 2.2 kWh	75,000 to 100,000 Bill US$	100 %
Industrial. Countries of Today	**1.5 - 2**	1 US$/ 1 to 2 kWH	1/2	40 %
Develop. Countries of Today	**7 - 7.5**	1 US$/ 1 to 5 kWh	1/2	60 %

YEAR 2050

Present Level ⇔	1	0.5	1 to 2	11 to 15	**14** to **18** Bill. t OE
Cost of Renew. E.	Other Renewable	Hydro	Nuclear	Fossil	**Total PE**
Strongly Reduced ⇔	Few to Many	0.5	1 to 2	12 to 16 minus other renew.	**14** to **18**

(Numbers on PE, GDP, GDP/PE have been taken respectively deduced from [IEA, WEC] and from the country reports, see appendix 2.)

Until about 2050

Taking into account the differences to be expected of further growth of population and of speed of further economic development in already highly industrialized countries and in still less industrialized developing countries the share of the global GDP - at least about twice as much as today or more - between both types of countries may become about equal. The global demand of (commercial) primary energy may increase at least by about 50 to 100 percent.

Especially in countries with further strong and fast economic development to properly improve the life of their people soon the more or less restricted availability of sufficient energy at sufficient low cost will be a severe limiting factor to further economic development.

Concerning the further availability of fossil fuels the conventional and still relatively cheap reserves are more or less limited (see table 2). At present rates of use, coal will last about 300 years, natural gas about 70 years and oil about 40 years. Furthermore these oil and gas reserves are rather unequally dispersed around the globe: about 2/3 of the reserves of crude oil are concentrated in the Middle East countries, the reserves of natural gas are concentrated in the Middle East countries (about 30 percent) and in the countries of the former Soviet Union (about 40 percent). Only the reserves of coal are distributed more or less equally around the globe.

At the present status of energy technologies the future provision of energy from non fossil energy sources is more or less rather limited,

- either because of limited availability (e.g. hydro power)
- and/or because of relatively high investment cost (e.g. nuclear fission power)
- or because of high respectively very high investment cost and missing availability of energy storage (e.g. wind power and photovoltaics).

Therefore fossil fuels are expected to continue to be the dominant source of primary energy at least within the next decades despite the danger of climate change.

To reconcile both confronting necessities

- to provide sufficient energy
- and to reduce further emissions of carbon dioxide from burning of fossil fuels

requires strong efforts on both

- R & D on <u>non fossil energy technologies</u>

    - nuclear fission
    - renewable energy
    - nuclear fusion

    to gradually substitute the further use of fossil fuels within some to many decades

- R & D on clean fossil energy technologies
    - increasing the efficiency of power plants
    - including CO_2 sequestration and deposition

to allow fossil fuels to still be the major source of primary energy within the next decades.

This will require paying special attention

- to the different intentions of different countries to further develop favoured special energy technologies

- to corresponding scientific and technical possibilities

- and to international cooperation in R & D.

TABLE 2: FOSSIL FUELS

	ANNUAL CONSUMPTION AT PRESENT (2000)	RESERVES (CONV.) PROVEN AVAILABILITY FOR ECONOMIC EXPLOITATION	RESOURCES (CONV. + UNCONV.) ESTIMATED AVAILABILITY WITHOUT REGARDING COST FOR EXPLOITATION
COAL	3.4 BILL t CE	1,000 BILL t CE	6,000 BILL t CE
OIL	3.6 BILL t OE	130 BILL t OE	650 BILL t OE
NATURAL GAS	2.5 TRILL Nm^3	165 TRILL Nm^3	500 TRILL Nm^3
METHANE HYDRATES	-	-	1,500 TRILL Nm^3 R & D*
TOTAL	8.0 BILL t OE	967 BILL t OE	21,000 BILL t OE
	[IEA]	[IEA]	[IEA + BGR]

* Presently some countries (e.g. U. S. A., India, Japan) investigate [G. Bohrmann, R. Matsumoto, K. Sain]
– the resources of methane hydrates especially in the sediments of continental sea shelves
– a possible exploitation of these resources
– the danger of release of methane from these resources into the atmosphere

3. Summaries of R & D on energy technology reports from experts

3.1 Fossil fuels

The main efforts of R & D are concerned with

- fossil fuel fired power plants (3.1.1)
  (affecting 40 percent of fossil fuel consumption at present) to increase efficiency of producing electric power and to sequester and deposit carbon dioxide)
  [expert: Olaf Bolland, Norway]

- fossil fuel fired high temperature fuel cells (3.1.2)
  [experts: H. Yokakawa, K. Tanimoto, Japan]

- liquid fossil fuels in transportation sector (3.1.3)
  (affecting 24 percent of fossil fuel consumption at present)
  here conversion of natural gas to methanol
  [expert: Jon Samseth, Norway]

- non conventional resources (3.1.4):
  methane hydrates in sediments of continental sea shelves:

  concerning the risk of release of large amounts of methane into the atmosphere amplifying global warming
  [expert: G. Bohrmann, Germany]

  concerning a possible exploitation of these resources
  [experts: K. Sain, India, and R. Matsumoto, Japan]

3.1.1 Fossil fuel fired power plants including CO_2 sequestration and storage (O. Bolland, Norway)

Further development of the technologies of fossil fuel fired steam and gas turbine power plants especially to work at higher steam and gas inlet temperatures mainly by designing and producing new materials is expected to increase efficiency of converting high temperature heat to electric power significantly (by about 5 to 10 percent points).

But implementation of CO_2 sequestration partially via innovative methods, like membrane technologies, leads to a reduction of the overall conversion efficiency of the power plant

- via post combustion CO_2 sequestration by about 9 percent
- via pre combustion CO_2 sequestration by about 7 percent
- via oxy fuel combustion CO_2 sequestration by about 14 percent.

Summarizing overview of the expected development of the efficiency of fossil fuel fired power plants [O. Bolland, COOR]:

		from at present		to finally	
		typical	at best	without CO_2 sequestration	with CO_2 sequestration
steam turbines		30 to 40	45	50 to 55	
gas turbines		30 to 40	42	40 to 45	
combined steam and gas turbines	coal fired		54	about 60	47 to 52
	gas fired		58	about 63	50 to 55
		[percent]		[percent]	

The CO_2 sequestered at the power plant can be deposited in depleted gas fields or in deep saline aquifer layers. The latter approach has been actively tested since 1996 with an annually injection of about 1 million tons of CO_2 into a saline aquifer layer about 800m deep under the coastal floor in the vicinity of the Sleipner Gas Field in the North Sea. (The available reservoirs for CO_2 deposition in this region would allow to store all CO_2 from power plants all over Europe produced within 100 years and more.) At present the cost of electric energy from modern fossil fuel fired power plants amounts typically to about 3 cents/kWh_{el}.

CO_2 sequestration an deposition in the way indicated above would imply additional cost of about 2 to 3 cents/kWh_{el}. A hypothetical sequestration and deposition of CO_2 from all fossil fuel fired power plants around the globe, providing at present annually about 10 PWh electric energy, would imply an increase of cost for electric power by about 200 billion US$/year. This cost may be compared to the cost of global damage by the onset of climate change of at present about 200 billion US$/year with an expected rise to 1000 billion US$/year and more within the coming decades without measures to restrict climate change by reducing further CO_2 emissions.

3.1.2 Fossil fuels fired high temperature fuel cells (H. Yokakawa and K. Tanimoto, Japan)

On a time scale of about 1 to 2 decades high temperature fuel cells, Solid Oxide Fuel Cells, SOFC, (H. Yokokawa) and Molten Carbonate Fuel Cells, MCFC, (K. Tanimoto) are expected to become available economically attractive with efficiencies of about 50 to 60 percent. With fuel cells of these types electric power could be provided both decentralized (possibly in combination with micro turbines) as well as centralized (possible in combination with gas and steam turbines).

3.1.3 Liquid fuels in the transportation sector: conversion of natural gas to methanol (J. Samseth, Norway)

At present about 24 percent of fossil fuels are consumed for propulsion in the transportation sector. The technologies to convert natural gas to methanol and to liquify coal to methanol and/or gasoline are available. In future - when cars with fuel cell electric motors may become available (see section 3.5) one might consider providing hydrogen (see section 3.4) for driving fuel cells from the fossil fuels with sequestration of CO_2 and its deposition (*S. Richter and U. Wagner, Germany*).

3.1.4 Non conventional resources of fossil fuels: methane hydrates in sediments of continental sea shelves (G. Bohrmann, Germany, R. Matsumoto, Japan, K. Sain, India)

The amount of methane hydrates especially in the sediments on the sea floor of continental sea shelves has been estimated to about 1,500 trillion Nm^3, corresponding to 12,000 billion t_{oe}, about twice as much as the total conventional and non conventional resources of coal, oil and natural gas.

Concerning the possible release of methane from these sediments in the atmosphere (G. Bohrmann):

The stability of these gas hydrates sediment deposits is only given within a narrow band of temperature and water pressure at the sea floor. Small changes of temperature and pressure can lead to a destabilisation of these sediments and to corresponding release of methane finally into the atmosphere. As methane is a very climate sensitive gas such a release could increase greenhouse warming on earth significantly.

Concerning the exploration of methane hydrates and R & D towards commercial exploitation (K. Sain, India, R. Matsumoto, Japan):

Exploration of marine gas hydrates are pursued via seismic survey, offshore exploration drilling and geochemical investigations. Different methods towards a possible economically viable mining like e.g. local depressurisation and inhibitor injection are pursued together with proper hazard assessment.

3.2 Nuclear fission energy

At present about 16 percent of the global demand for electric power are met via nuclear fission power plants in 30 countries with nuclear power plants providing from a few to about 80 percent of the local demand for electric power.

All relevant technologies for allowing a fairly economical use of nuclear fission energy in an environmentally safe way are available, at least in principle. This holds for the whole chain of processes, from mining uranium deposits, operating nuclear power plants inherently safe with respect to the nuclear fission chain reaction as well as to the removal of the after-heat from radioactive decays after the stop of the nuclear chain reaction without any risk of a large accident (High Temperature Reactor, HTR), to finally the safe deposition of radioactive waste.

At present R & D on evolutionary improvements of nuclear power plants, NPP, to be built within the next decades (generation III NPP) are underway

- to further decrease the risk of large accidents of Light Water Reactors, LWR (main activities in USA, France, Japan)

- to avoid the risk of a large accident totally with HTR, inherently safe in any respect by physical principles (main activities in China, South Africa, USA, and Russia, Japan)

Furthermore R & D on revolutionary improvements of NPP to become available after many decades of further development (generation IV NPP) are studied at present, to finally develop most suitable technologies to allow provision of nuclear fission energy by very large amounts and this over a time period of at least many hundred years heading for nearly closed fuel cycle via breeding and reprocessing of fuels and heading for reducing the amount of high level radioactive waste largely either by burning all actinides in proper NPP or by transmutation of minor actinides to shorten the lifetime of radioactive waste:

- Very High Temperature Reactors, VHTR (with special emphasis on provision of hydrogen by thermo chemical catalytic water splitting)

- Supercritical Water cooled Reactors, SWR

- Lead and Sodium cooled Fast neutron Reactors with breeding potential, LFR and SFR (heading finally for nearly closed fuel cycle)

- Gas cooled Fast Reactors, GFR, and Molten Salt Reactors, MSR, including burning of actinides from radioactive waste possible with Accelerator Driven Systems, ADS

- Transmutation of minor actinides from high level radioactive waste either by bombardment with neutrons from a nuclear reactor or from a particle accelerator or e.g. by photo transmutation via laser driven high brightness gamma ray beams [LED].

(These investigations are mainly pursued in an international cooperation within the Generation IV International Forum of - at present - 10 countries: USA, France, Japan, South Africa, UK, Canada, South Korea, Argentina, Brazil and Switzerland, and furthermore EURATOM. Further countries like e.g. China and India exhibit high interest in these developments.)

(A. C. Kadak, N. E. Todreas, B. Richter, USA, M. Igashira, Japan)

- Thorium fuelled advanced Heavy Water Reactor, ThHWR, and possibly other reactor types as well

(Main activities in India.)

(K. Anantharman and R. K. Sinha, India)

Furthermore to enlarge the availability of uranium fuel (from at present some 100 years to possibly many 1000 years) an economic way to extract uranium from sea water is investigated in Japan.

(N. Seko and M. Tamada, Japan)

The main challenge in all the further development of nuclear fission power technologies is to achieve solutions both technically and economically highly attractive, and this in environmentally safe ways.

3.3 Renewable energy

Before industrialisation renewable energy had been the only source of energy available

- firewood to provide heat
- biomass for food, for horses and other animals for hauling transportation vehicles
- wind for propulsion of sailing boats
- wind and water power to run mills.

The onset of industrialisation caused an extraordinarily fast rise of the demand on energy, caused a severe shortage of firewood in many countries. Fossil fuels soon became the dominant source of primary energy. The abundant and steady availability of fossil fuels and especially their low cost satisfied the newly arising additional demand on energy to provide any required fast rising amount of

- heat
- electric power
- fuels for propulsion in the transportation sector.

At present renewable energy can be used to provide only a rather limited amount of secondary energy, for instance

	via	percentage of global demand	
electric energy	hydro power wind power biomass geothermal sunlight	18 0,3 1 0,3 0,02	20 percent
fuels transportation sector	ethanol biodiesel	about 1 about 1	2 percent
heat (mainly for cooking in developing countries)	burning non commercial biomass (mainly firewood)	about 7 percent of the total global demand on primary energy	

A more extended use of renewable energy at present is mainly handicapped

- by restricted availability (e.g. hydro power, biomass)
- by strongly fluctuating and intermittent availability of hydro river and wind power and of sunlight (see fig. 1 [STRO, WAG, GOE])
- by comparatively high investment cost and cost of energy provided (e.g. sunlight, geothermal energy).

This is a challenge for R & D making best use

- of interdisciplinary science and technology
- of nano sciences and nano technologies for design and production of new materials

to achieve economically attractive solutions, as indicated in the following survey of reports from scientific experts.

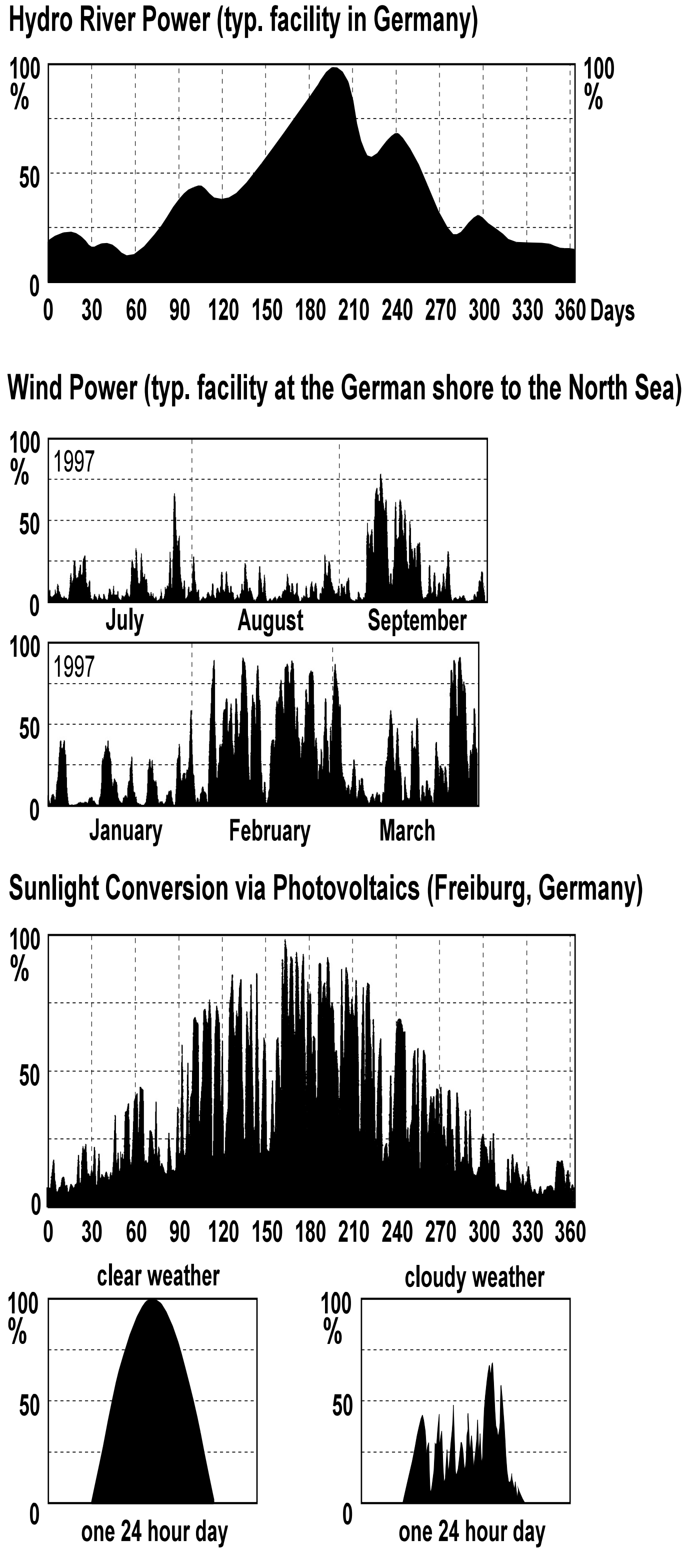

Figure 1 Availability of Electric Power from River Hydro [STRO], Wind [WAG] and Photovoltaic [GOE] Powerplants: Restrictions and Fluctuations in Time

3.3.1 "Solar" electric energy via photovoltaics, PV
(A. Luque, Spain)

Further R & D on PV is pursued

- on well established roads of mainly Si and furthermore Cu_2S, $Cu(InGa)Se_2$, CdTe technologies

- on completely new paths, including organic solar cells, to achieve much higher efficiencies and this at much lower cost

- on installing PV power systems in space in geostationary orbit - by innovative, sufficiently low cost space shuttle technologies -, thus to allow continuous provision of electric power, being transmitted to earth via microwaves directed onto ground based receiver antennas
(H. Matsumoto and N. Shinohara, Japan)

3.3.2 Storage of electric energy
(J. Ahearne, USA)

Intimately connected to solar electric energy via PV on earth is the required storage of electric energy

- either directly in rechargeable batteries hoping to finally achieve much higher storage densities and this at much lower cost than at present

- or indirectly e.g. via producing and storing hydrogen (chapter 3.4) to be later used in fuel cells (chapter 3.5) to produce electric energy

Energy storage technologies - at present commercially available - are mainly Pumped Hydro Storage (globally 56 units with a total power of about 140 GW, corresponding to about 4 percent of the total installed power) and furthermore underground Compressed Air Energy Storage (2 units with a total power of 0.4 GW). These large scale energy storage technologies are most suitable for daily partially balancing the supply of electric power during the hours of high and of low demand.

3.3.3 Solar thermal power plants, STPP
(M. Romero, Spain)

In solar thermal power plants - to be positioned in low latitude arid desert regions with high insolation - sunlight is concentrated via large area mirrors and converted to high temperature heat (of hot air or hot vapour) to then drive gas or steam turbines to produce electric power. With forthcoming possibilities of cheap storage of high temperature heat e.g. in sand STPP could provide electric power continuously, in plant units of up to about some 100 MW_{el}.

A further option of STPP, the Solar Chimney PP is based on the idea of heating the air inside a largely extended greenhouse and letting escape the hot air through a high chimney in the center of the greenhouse. Inside the chimney the upward draft drives a wind rotor generator. At present a 200 MW_{el} demonstration plant with a circular greenhouse of 7 km diameter and a chimney of 1 km height is planned to be built near Mildura, Australia [BER].

3.3.4 Wind power plants
(H.-J. Wagner, Germany)

The technology of wind rotor generator plants with up to a few MW max. electric power is well advanced. Major further R & D is concentrated on the development of wind rotor generator units with some MW max. electric power to be installed “offshore” in shallow ocean regions to extend the intervals of providing electric power from typically up to about 20 percent of availability in time - typical for on shore and inland wind rotor installations - to about 30 to 40 percent.

3.3.5 Hydro power

Concerning hydro power

- the technologies of high pressure reservoir and low pressure river power plants are well established [PUER, STRO, YUAN]

- the technology of tidal power plants is available in principle and has been investigated comprehensively [WAL]. But its further realisation beyond the existing 240 MW tidal power plant at the Rance estuary in France has been barred mainly by the rather high expenses to be expected.

- the technologies of ocean wave and ocean current power conversion still require extensive R & D both for large power facilities to be installed in the open ocean as well as for small power facilities to be installed in shallow coastal areas.

3.3.6 Biofuels
(R. C. Cerqueira Leite, Brazil)

For providing ethanol from sugar cane in Brazil an energy efficiency ratio, - the ratio of the caloric energy of the biofuel to the total energy input for growing biomass and its conversion to biofuel - of about 8 has been obtained. For producing ethanol, methanol or biodiesel from other kinds of biomass the energy efficiency ratio obtained so far is much lower.

To provide biofuel from biomass may be rather promising for countries with proper large areas of land suitable for agricultural energy crops at present like e.g. Brazil. On a global scale the bottle neck for providing a large fraction of the demand on liquid fuels for the transportation sector is the limited availability of sufficient areas for agricultural land to provide sufficient amounts of food for a world population, expected to rise from about 6 to at least about 9 billion humans.

To further enlarge the total area of agricultural land by a significant amount extensive R & D is required towards recultivation of sufficiently large areas of arid land including the provision of water for artificial irrigation by desalination and purification - this at sufficiently low cost -, this artificial irrigation at least for some time, till the recultivation to green land may change the local climate to obtain sufficient natural precipitation.

3.3.7 Geothermal energy

The use of the rather limited resources of geothermal energy from natural hot water and vapour wells as well as the withdrawal of hot water from deep aquifer layers via artificial bore holes is established. Rather limited R & D is pursued to withdraw heat from deep hot dry respectively wet rock layers - e.g. in Soultz-sous-Forêts in France - via drilling boreholes into 3 to 5 km depth, impressing water through one of the boreholes and to withdraw vapor at temperatures of 120 to 200 degrees Celsius through a second borehole [CLA].

3.4 Hydrogen

(W. E. Evenson, USA, S. Richter and U. Wagner, Germany, M. Ogawa, Japan, J. Samseth, Norway, C. Beckervordersandforth, Germany)

Hydrogen is a secondary energy carrier to possibly be provided from any type of primary energy respectively of secondary energy like electric energy or high temperature heat. At present about 50 million t hydrogen/anno (with a caloric value corresponding to 140 million t oe or about 10 percent of the present demand on liquid fuels in the transportation sector) are produced globally from natural gas. The provision of hydrogen in the chain electrolysis, liquefaction, storage and distribution requires the expenditure of at least 2 kWh electric energy for 1 kWh caloric energy of hydrogen provided. Therefore a provision of large amounts of hydrogen via electrolysis would require a corresponding large rise of the demand on electric energy.

For future provision of hydrogen by large amounts rather challenging R & D along different new ways is required and is partially already going on, e.g.

- photo electrolysis (by special PV cells)
- solar thermal
- photo chemical - catalytic
- photo biological - water splitting
- thermo chemical

To provide hydrogen as an innovative fuel in the transportation sector to a large scale economic solutions for stationary and mobile storage, handling, transportation and distribution have yet to be found.

As an alternative to the difficult handling of hydrogen R & D towards converting hydrogen directly at the location of its production via synthesis with CO_2 extracted from the atmosphere to a proper synfuel like e.g. methanol may finally lead to avoid the expensive infrastructure of a future hydrogen economy [LACK].

3.5 Low temperature fuel cells

(C. Cremers and U. Stimming, Germany)

Low temperature fuel cells, especially Polymer Electrolyte Membrane Fuel Cells, PEMFC, and Direct Methanol Fuel Cells, DMFC, are regarded as forthcoming future technologies for mobile provision of electric power especially on board of fuel cell electric motor vehicles.

Further challenging, rather imaginative R & D is required to overcome the many difficulties at present, especially

- to improve membrane materials for higher operation temperatures
- to improve the catalyst structures
- to increase conversion efficiency
- to achieve higher power density
- to improve systems designs
- to enlarge choice of useable fuels
- to take into consideration bio-electrochemical fuel cells
- and last not least to reduce the cost of fuel cells by up to 2 orders of magnitude to become competitive with present vehicle propulsion by internal combustion engines.

3.6. Nuclear fusion energy

(R. Fonck, USA, P. K. Kaw, India, C. Hidalgo, Spain, B. Richter, USA, K. Mima, Japan)

Concerning the possible use of *nuclear fusion energy* by means of nuclear fusion power plants, up till now only fusion processes in principle, rather limited in power and in operation time have been achieved so far.

Further necessary steps of the technology development of nuclear fusion power plants are

- to achieve the necessary high fusion power over sufficient long operation time
- to develop proper materials with sufficient stability for the first wall of the fusion vessel
- to extract the rather high thermal power from the walls of the fusion vessel
- to breed the necessary tritium fuel for fusion by neutron lithium interactions inside the walls of the fusion vessel and to extract it
- finally to prove the technology of a nuclear fusion power plant to be sufficiently economic.

To achieve these goals required rather different options of fusion technologies are pursued at present:

- magnetic confinement of the hot fusion plasma, initially heated up with HF and neutral atom beams (TOKAMAK : ITER, STELLARATOR)
- inertial confinement of the fusion plasma initially heated up with lasers and laser generated x-rays, with “z-pinch” electric pulse generated x-rays, with heavy ion beams.

And there may be further options initiating fusion to become available like e.g. muon catalytic fusion including the recovery of muons sticking to helium nuclei produced by fusion of deuteron and tritium nuclei [NAG] or initiating the heating of a fusion plasma via standing acoustic waves leading to strong compression shock waves [TAL].

To achieve the goals via any of these options at least 2 to 3 further successive steps of R & D are required mainly at test facilities and demo plants. Each step is rather expensive in manpower and cost and will require a time span of 1 to 2 decades for construction and operation. The high expenditures call for international collaborations to pursue these options.

The option most advanced at present is Magnetic Confinement Fusion with a Tokamak device: The International Thermonuclear Experimental Reactor, ITER, is the next step along this line and is being planned by an international collaboration of scientists and engineers from the European Union, Japan, Russia, USA, China and South Korea.

Hopefully all possible promising options of fusion technologies will be pursued until at least one of them has led to a viable technical as well as economical solution.

4. Conclusions - outlook

It is an important and exciting task of physics concerning R & D on energy technologies, to discover and prepare new ways based on brilliant ideas, making use of computational physics, nano sciences and nano technologies to provide any secondary energy demanded from any kind of primary energy

- in sufficient amount
- in an environmentally safe way, especially
  - on one hand to fight climate change and to limit respectively to avoid the threatening high cost of damages by climate change
  - on the other hand to reduce respectively to avoid the risk of large accidents at nuclear power plants
- at sufficient low cost

meeting the still rising demand on energy mainly caused by economically fast developing countries where the restricted availability of energy is a limiting factor for further development.

A large variety of energy technologies can be tackled by challenging R & D covering nearly any branch of modern physics, never restricted to one branch alone, always basic physics and applied physics linked together inseparably.

R & D of some of these technologies may require investments of only some 100 human years (like possibly innovative PV and battery storage). Others may require investments of some 100,000 human years (like fusion power and PV power in space). Nevertheless all of these technologies have to be investigated further.

There is high interest in any of the innovative energy technologies in many countries around the globe including OECD countries as well as especially countries with high and still fast rising populations like e.g. China, India, Brazil. (These 3 countries together - representing at present 40 percent of the world population - cause already nearly 20 percent of the global demand on energy. And this share my well increase to about 50 percent within the forthcoming decades.)

Different countries put different emphasis on improving the use of the different sources of primary energy, fossil fuels, nuclear fission, renewable energy and nuclear fusion. But all countries look for appropriate scientific cooperation in R & D of energy technologies of their choice.

To be kept in mind: Fossil fuels will continue to be the dominant source of primary energy at least within the next few decades. It will take some to many decades to improve the use of other sources of primary energy like e.g. nuclear fission and renewable energy to be able to play a much more important role to satisfy our demand on energy than nowadays. This is intimately linked to the ability to cut cost of providing energy from nuclear and especially from renewable energy appreciably, and - concerning the increased use of renewable energy with strongly intermittent availability - to find new ways to store energy - especially electric energy - efficiently and cost effectively.

Nuclear fusion energy may become an option only in the far more distant future of many decades. Therefore R & D on clean fossil fuel technologies with highest possible efficiencies and including CO_2 sequestration and storage respectively use is of utmost importance.

5. List of expert reports on R & D of special Energy Technologies

I. Fossil Energy

1. Power Generation with CO_2 Capture and Sequestration

   by **Olaf Bolland**, Norwegian University of Science and Technology, Trondheim, Norway

2. CO_2 Capture and Sequestration

   by **Olaf Bolland**, Norwegian University of Science and Technology, Trondheim, Norway

3. Future needs for fundamental research in the oil and gas industry especially on non conventional resources

   by **Jon Samseth**

4. Conversion of Natural Gas to Methanol

   by **Jon Samseth**

5. Oceanic Hydrates, a dynamic reservoir of methane within the marine environment

   by **Gerhard Bohrmann**, Department of Geosciences, University of Bremen, Germany)

6. Methane Hydrates: Present Status of worldwide R & D on the utilisation of Gas Hydrates for Power Production

   by **Kalachand Sain**, National Geophysical Research Institute, Hyderabad, India

7. Exploration of Marine Gas Hydrates around Japanese Islands

   by **Ryo Matsumoto**, Earth and Planetary Science, University of Tokyo, Japan

II. Nuclear Fission Energy

1. New Nuclear Energy Plant Designs

   by **Andrew C. Kadak**, MIT, Cambridge, US

2. R & D Needs of Fission Energy Generation

   by **Neil E. Todreas**, MIT, Cambridge, US

3. Physics Based R & D for Innovative Fission Reactors

   by **Masayuki Igashira**, Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Japan

4. Present Status of worldwide R & D on the Utilisation of Thorium for Power Production

   by **K. Anantharaman** and **R. K. Sinha**, Bhabha Atomic Research Center, Trombay, Mumbai, India

5. Proper Handling of Radioactive Waste - The US Transmutation Program

   by **Burton Richter**, Stanford, US

6. R & D towards Recovery of Uranium from Sea Water

   by **Noriaki Seko** and **Maseao Tamada**, Takasaki RCRE, JAERI, Japan

III. Renewable Energy

1. R & D Needs in Photovoltaics

   by **Antonio Luque**, Universidad Politécnica, Madrid, Spain

2. Storage of (Electric) Energy:
   - Batteries: Present and Future
   - Pumped Hydro and Compressed Air Energy Storage

   by **John Ahearne**, Research Triangle Park, NC, US

3. Space Solar Power Systems: Development Status and Future Perspectives

   by **Hiroshi Matsumoto** and **Naoki Shinohara**, Research Institute of Sustainable Humanosphere, Kyoto University, Japan

4. Solar Thermal Power Plants

   by **Manuel Romero**, CIEMAT, Madrid, Spain

5. Energy from Biomass

   by **Rogerio C. de Cerqueira Leite**, Universidade Estadual De Campinas, Brazil

6. R & D on Wind Power Plants, especially offshore

   by **Hermann-Josef Wagner**, LEE, Ruhr-Universität Bochum, Germany

IV. Hydrogen

1. The Potential for the Hydrogen Energy Economy

   by **William E. Evenson**, Brigham Young University, USA

2. R & D towards Provision of Hydrogen

   by **Stefan Richter** and **Ulrich Wagner**, Forschungsstelle für Energiewirtschaft und Technische Universität München, Germany

3. Report on the Thermochemical Water Splitting (via the Iodine Sulphur Cycle) at the HTTR

   by **Kaoru Onuki** and **Masuro Ogawa**, JAERI, Japan

4. Hydrogen Production and Storage

   by **Jon Samseth**, SINTEF, Norway

5. Use of Natural Gas Pipelines to Transport Hydrogen Gas
   by **Christian P. Beckervordersandforth**, Ruhrgas AG, Essen, Germany

V. Fuel Cells

1. Low Temperature Fuel Cells: Development Status and Future Perspectives

   by **Carsten Cremers** and **Ulrich Stimming**, Bavarian Center of Applied Energy Research, TU Munich Germany

2. Solid Oxide Fuel Cells

   By **Harumi Yokakawa**, National Institute of Advanced Industrial Science and Technology, AIST, Japan

3. Technolgical Status of Molten Carbonate Fuel Cell

   by **K. Tanimoto**, National Institute of Advanced Industrial Science and Technology, Japan

VI. Nuclear Fusion Energy

1. R & D Opportunities for Fusion Energy

   by **Ray Fonck**, University of Wisconsin, Madison, USA

2. Fusion Energy using TOKAMAKs

   by **Predhiman K. Kaw**, Institute for Plasma Research, Bhat, Gandhinagar, India

3. Physics Issues on Magnetically Confined Plasmas: Stellarator Devices

   by **Carlos Hidalgo**, EURATOM-CIEMAT, Madrid, Spain

4. Status Report on Inertial Confinement Fusion

   by **Burton Richter**, Stanford University, USA

5. Report on Laser Fast Ignition for Inertial Fusion Energy

   by **Kunioki Mima**, Institute of Laser Engineering, Osaka University, Japan

6. List of country reports on their special energy situation

P. R. China	by Huo Yuping
India	by P. K. Kaw
Brazil	by R. C. Cerqueira Leite
USA	by J. F. Ahearne
Russia	by O. N. Favorskyi
Japan	by Y. Nagai
Germany	by K. Heinloth
France	by H. Nifenecker
Southern European Countries (Italy, Spain and Portugal)	by F. Yndurain, Spain
Nordic European Countries (Iceland, Norway, Denmark, Sweden, Finland)	by J. Samseth, Norway

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WEC World Energy Council, 2004

YUAN Yuan Dafu, Tian Ziqin, Wang Shuqing, Mechanical and Electrical Design of the Three Gorges Project, in HEI, Subvolume C

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