

THE GLOBAL ENERGY PROBLEM

*by*

Professor Lennart Bengtsson

*Reprinted from*

ENERGY &  
ENVIRONMENT

VOLUME 17 No. 5 2006

MULTI-SCIENCE PUBLISHING CO. LTD.  
5 Wates Way, Brentwood, Essex CM15 9TB, United Kingdom

## THE GLOBAL ENERGY PROBLEM

**Professor Lennart Bengtsson**

*ESSC, University of Reading, UK*

*Max Planck Institute for Meteorology, Hamburg, Germany*

*lennart.bengtsson@zmaw.de*

### 1. INTRODUCTION

To satisfy the world's need of energy is one of the greatest challenges for the 21st century. And to satisfy the energy needs the world has in an increasing degree become dependent on fossil fuel. This has been possible to achieve in an economical reasonable way thanks to easily exploreable sources of oil, natural gas and coal and efficient methods to transform this basic energy into usable forms such as electricity. The contribution from regenerative energy sources (solar, wind, water and biomass burning) provides only a smaller contribution and as we highlight in this paper is likely to do so even in the foreseeable future.

There are two related issues, which the world community must address in the long term. One is the limited resource of accessible fossil fuels and the second the increase of carbon dioxide in the atmosphere mainly caused by the burning of fossil fuels. And this must be addressed with the awareness of the fact that many countries of the world today are insufficiently supplied with energy. In fact it is the lack of suitable energy, such as electricity, which is one of the most serious obstacles to a better life for a large part of the world's population. The lack of fresh water in parts of the world is also expected to worsen increasing the need of energy for desalination plants.

We are clearly fast reaching a critical phase in human global development, and that phase is centred upon the use of energy. It is an issue upon which scientists around the world must clearly take a lead in resolving. The basic components of the problem are easily stated. Human social development over the past two centuries has been largely due to the availability and use of abundant supplies of energy, primarily in the form of carbon fuels - coal, oil, and gas. The balance of evidence suggests that the burning of these substances is having a direct effect on global temperatures and thus, in turn, in changes to the global climate, the extent of which are difficult to predict. Accommodating to such changes (whatever they are) will, however, require more energy per capita. But this is only part of the problem. Even if all of the fossil fuels were to be burned, they will not sustain the current and anticipated energy demand for very long. Supplies of oil and gas are unlikely to last beyond the end of this century at current rates of consumption. And if the current and future populations are to enjoy the same standard of living as is currently enjoyed in the western world, the current energy use per capita elsewhere will have to be increased. And this is not only a human issue. If what is left of the natural environment is to be maintained, and human impact

minimised (as, for example, by the reuse, recycling of materials; the production, manufacture, and transport of chemicals, goods, and materials with near zero release of industrial effluents) then the per capita use of energy in much of the world needs to be much higher than at present. So where is this energy to come from, because it will be needed in the very near future?

## 2. THE ENERGY PRODUCTION

The world's total production of primary energy (TPES) has increased from 72PWh to 121PWh between 1973 and 2002 almost following the total world population (IEA, 2004). 1PWh is equal to 3.6EJ. The annual energy production per capita is ca. 20 MWh. The projected increase until 2030 is 190 PWh. The projected growth is faster than the expected population increase (medium fertility) corresponding to a production per capita of ca 22 MWh in 2030.

The energy production is dominated by fossil fuel (coal, oil and gas), which amounts to over 80%, burning of wood and waste by some 10%, hydro-electrical and nuclear power by about 7%. The contribution from geothermal, solar, wind etc. amounts to about 0.5%. Table 1 summarises the energy content in different kinds of fuel.

The relative contribution from the different energy sectors has changed only slightly between 1973 and 2002, except for an increase in the contribution by nuclear power by 1 to 6%.

**Table 1**

The following is approximately required to produce 1 PWh/year

- 
1. 90 Mt oil
  2. 140 Mt coal
  3. 95 Gm<sup>3</sup> natural gas
  4. 9 000 km<sup>2</sup> solar panels (radiation conditions typical for US)
  5. 150 000 wind generators (3 MW capacity, placed in areas with suitable wind conditions and effectively used 25% of the time)
  6. 330 Mt biomass (ca 40% water content)
  7. 6 Kt Natural Uranium (0,7% enrichment)

The total energy consumption (TFC) amounts to some 68% of the total production mainly due to losses in the generation of electricity from fossil fuel and other conversion processes as well as loss of heat from nuclear power stations. Only about a third of this energy is converted to electricity. Because of the more rapidly growing use of electricity (3.4% annually) the primary energy production has been increasing slightly faster (1.8% annually) than energy consumption totally (1.5% annually). However, in order to simplify the presentation here we will be using TPES in the following unless otherwise stated. In comparing the different sources of energy it is required to apply a systematic conversion. We have applied the net caloric values for different kind of energies as used by OECD as well as their method for estimating the energy content of electricity. As a suitable energy unit we use 1 PWh/year. Figure 1

summarises the energy use in 2002 and percentage change between 1973 and 2002. Electricity production and its use are included specifically.

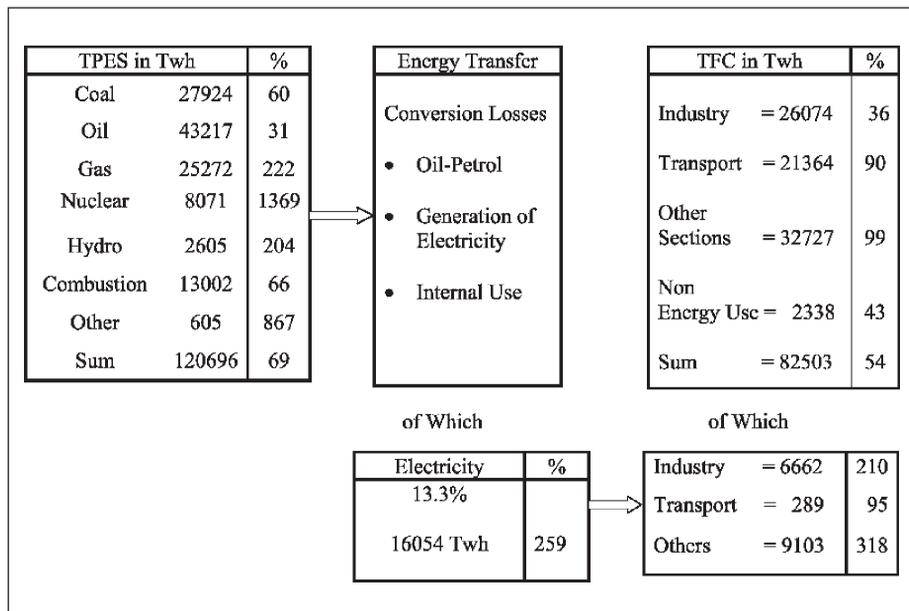


Fig 1 Global energy use in 2002 and the percentage change between 1973 and 2002. TPES is the production of primary energy and TFC the total energy consumption.

TPES per capita is most unevenly distributed between countries with a variation by almost two orders of magnitude. The OECD countries have values which are between 2-6 times the global averages while several countries in the third world have less than a quarter of the world average (Haiti for example with less than 3 MWh/person).

It is interesting to note the relative high values for the Nordic countries (some 65 MWh/person) as well as for developed countries in the tropics. (Singapore 71 MWh/person)

It seems that there is a clear relation between a higher standard of living and the TPES/capita. Additional factors are due to climate conditions (need for heating as well as for cooling), industrial activities and need for transport of goods and services. The relatively high value in United States, for example, (93 MWh/person) is influenced by both adverse climate conditions (need for warming in the winter and cooling in summer) and by a higher need for local transport compared to many countries in Europe. However, the scope for energy savings is probably higher in the United States.

The purpose of this note is to discuss the severe energy problem, which the world will be facing in the next decades. While it seems feasible that food can be produced to satisfy the majority of the world population the need for energy to create reasonable

living conditions, also for the poor countries, is likely to be more difficult to satisfy. We will also demonstrate the importance of a proper supply of suitable energy is required for the preservation of the environment. Malthus concern “that humans had the potential for steady growth, but the food production had not” can perhaps now be extended to energy (Bartlett, 2004) as today energy production in its present form does not have the capability for steady growth. Oil resources at acceptable cost are limited and so are other sources of fossil fuel. Increasing prices of fossil fuels are likely to lead to some reduction in the consumption in the industrialized countries but the need elsewhere, driven by the demand to improve standard of living, is likely to more than compensate for the energy saving in the rich countries. While we agree that the greenhouse issue is a severe problem for the world in the long perspective, we are afraid that the energy problem could be well as severe and if not being properly and timely addressed may lead to acute economical and social/political problems for the world. And furthermore, we believe the solution of the latter is a necessary condition for the solution of the former.

### **3. WHAT REALISTIC POSSIBILITIES EXIST TO REPLACE FOSSIL FUELS WITH OTHER ENERGIES?**

Nature provides energy in two basic forms. Firstly, the storage of fossil fuel and nuclear isotopes are limited by the fixed amount that exists on Earth. Secondly, solar energy is limited by the rate by which this energy can be captured. A subgroup of the Earth-stored energy is the geothermal energy mainly generated by radioactive emission from nuclear isotopes over a long period of time. In the solar energy we also include those forms of energy, which are created by solar energy on a time scale of a year or so. This includes wind and wave energy, hydro-energy, biomass (as created by photosynthesis) and stored heat in water and in the ground. This heat is being returned to space but could be used for additional heating (cooling) in the cold (warm) season. The solar energy and its derivatives constitute what is called regenerative energy sources.

## **4 REGENERATIVE ENERGY**

### **4. 1 Direct solar energy**

Direct solar energy could be used for heating and for electricity generation. Solar energy for heating has limited use except to alleviate the need for heating in cold climates. The main interest is the conversion of solar energy into electricity using photovoltaic solar cells. The conversion efficiency is presently 10-20% (Weisz, 2004). Considering energy losses in transformers, power-equalization over time and efficiency losses for conversions or transmissions an area of ca. 9 000 km<sup>2</sup> of solar panels may be needed to generate 1 PWh/year based on solar radiation conditions typical for US (Weisz, 2004)

### **4. 2 Biomass energy**

Solar to biomass conversion is two orders of magnitude less efficient than photo voltaic cell conversion. It is estimated that some 60Gt carbon is produced annually through biosynthesis of which some 25% may be in a form suitable for energy

production. Modern agriculture can generate 1-1.5 Kt biomass /km<sup>2</sup> including the conversion of biomass to useful fuel, but will require a supply of reactive nitrogen. A more realistic figure is rather 0.5 Kt/km<sup>2</sup>. The generation of 1 PWh would thus require some 7-800 000 km<sup>2</sup> in sustainable biomass generation (Weisz, 2004).

Present global production of “bio-energy” amounts to some 13 PWh. This includes the use of biomass in different forms including waste (with contribution from fossil fuel derivatives). A large part of the biomass is used for heating and cooking in developing countries and where the biomass “harvesting” is often associated with environmental stress. Increasingly biomass is also being used for energy generation in the industrial parts of the world including electricity generation and production of bio-fuel. Sweden, for example, is annually producing 104 TWh (2003) or 17% of its total primary energy from biomass. The amount of biomass, which can be used for energy production, is difficult to estimate. Assuming as an upper limit that 25 % of vegetated land area of ca. 80Mkm<sup>2</sup> is set aside for biomass to be used for energy production this would mean a primary production capacity of some 25 PWh/year.

#### **4. 3 Hydro electricity**

Hydro-electricity provides presently 2.6 PWh/ year, which is about 16% of all electricity or some 2% of the total energy. The potential for future increase of hydroelectricity is modest as the number of major suitable installations is few. The huge Three Gorges installation in the Yangtze river is planned to provide some 0.16PWh/year when fully completed. Present global projections until 2030 maintain an overall proportion of ca. 2% of the total production. It should further be noted that the total energy from precipitation falling on land is actually slightly less than the present annual TPES! The optimum extraction is probably at most 6-8 PWh/year.

#### **4. 4 Wind energy**

The average density of wind energy generation through a full column of the atmosphere is about 3W/m<sup>2</sup> so wind “harvesting” is restricted to smaller areas of the Earth surface with favourable wind conditions. Modern wind turbines in good location can produce about 800 kWh of electrical energy per year for each square meter of wind disc. (Hill, 2002). Scaling this up means that we need some 150 000 wind generators of 3MW capacity in order to generate 1 PWh/year electrical energy. Considering transition of the energy into hydrogen gas or losses in transmissions etc. as the place of generation and use is not likely to coincide, could well double this figure. A specific problem with wind energy is the high variability in time, which means that wind energy must be supported by other systems capable of providing energy consistent with the occurring need. Present energy projections until 2030 suggest a modest proportional increase which hardly may come above 1% of TPES.

#### **4. 5 Geothermal energy**

Needless to say, the amount of heat available in the interior of the Earth is sufficient for all possible use in the foreseeable future. The problem is the low energy density and the high investments required to explore the heat at the great depth required in most areas. So far the use of geothermal energy has been limited and no major expansion is foreseen bringing the supply above 1% of TPES globally.

#### **4. 6 Tidal energy**

Tidal energy exploits the natural rise and fall of coastal tidal water caused principally by the interaction of the gravitational fields of the Sun and the Moon. Tidal energy has been investigated by some countries such as the French 240MW (ca. 0.5 TWh/year) plant in river Rance estuary, which now has completed more than 30 years of successful operation. It is estimate that some 3000 GW of energy is continuously available but only some 2% (60 GW or 0.125Twh/year) can potentially be recovered from the tides for electricity production. The total contribution is thus rather insignificant.

#### **4. 7. Regenerative energy summary**

The provision of energy from regenerative sources will be restricted due to practical reasons and to some extent also because of inherent limitations such as for hydro-electricity. The amount, which could finally be achieved, will probably be limited to some 15-20% of the total need or to say at most some 40 PWh/ year towards the middle of this century. Even this rather modest amount would require huge investment with substantial detrimental effect on the environment including huge dams, substantial areas covered with wind installations and solar panels and enormous areas set aside for biomass generation. And using the biomass for energy production would have potentially negative consequences for the forest industry. Burning of biomass emits carbon dioxide and would worsen the situation before a steady state situation is reached. Drawing increased energy from the biosphere would further reduce the terrestrial carbon sink, which in recent decades has contributed to reduce the increase of greenhouse gases in the atmosphere.

The amount of steel and concrete for building wind power installations for example sufficient to produce 1PWh of energy are not small and amounts to some 60 Mt and 200Mt respectively (O. Bengtsson, pers. information).

In summary a common problem with the regenerative energy sources is its relatively low energy density often requiring major interferences with the environment.

### **5. FOSSIL ENERGY**

#### **5. 1. Petroleum/Oil**

The world production of crude oil in 2003 amounted to 3712 Mt., having an estimated energy content of 41.5 PWh. The increase over the last 30 years has been about 0.9%/year. The outlined production in 2030 is 6 000 Mt. equivalent to 67.1 PWh. The proven reserves of crude oil as of Jan. 2003 (EIA, 2004) is estimated to some 150 Gt, but some analyses indicate reserves of twice this amount. At best it seems that crude oil with the anticipated use may last for 30-60 years but probably not very much longer.

#### **5. 2. Natural Gas**

The world production of natural gas in 2003 amounted to 2 719 Gm<sup>3</sup> with an energy content of 25.2 PWh. The outlined production in 2030 is 5 300 Gm<sup>3</sup> equivalent to 50.0 PWh or by an estimated increase of 2.5%/year. The proven reserves of natural gas are

estimated to 155-175 Tm<sup>3</sup> but could be larger by another factor of two. Estimated lifetime of these stocks with present anticipated use is 10-15 years longer than those for oil.

### **5. 3 Coal**

The world production of hard coal in 2003 amounted to 4038 Mt with an energy content of 30.0 PWh. The outlined production in 2030 is 5600 Mt providing 41.6 PWh. The proven reserves of coal are estimated to some 1000 Gt of recoverable anthracite and lignite.

Additional fossil residuals exist in oil shale or bitumen in different parts of the world. An efficient harvesting of the carbonaceous content in bitumen requires drastic measures and is likely to imply major environmental damages and proportionally high emission of CO<sub>2</sub>.

## **6. NUCLEAR ENERGY**

### **6. 1 Fission energy**

#### **Uranium**

The fission of an atom of uranium-235 produces 10 million times more energy than the combustion of one atom of carbon. Natural uranium is about 0.7% uranium-235, and the world's present measured geological resources of uranium, in the lower cost category (80US\$/kg) of being economically recoverable, are just over 3.5 Mt. The world's total stock of nuclear power reactors, with combined capacity of some 363 GWe, currently require about 67,000 tonnes of uranium from mines (or the equivalent from stockpiles) each year. Fuel burnup is measured in MW days per tonne U (MWd/t), and it appears that many countries are increasing fuel enrichment (eg from 3.3 to 4.0% U-235) and then burning it longer, such as from 33,000 MWd/t to 45,000 MWd/t. (Over the 18 years to 1993 the electricity generated by nuclear power increased 5.5-fold while uranium used increased only just over 3-fold, according to the Uranium Information Centre Ltd.) Thus this stock will only last about 50 years.

However, according to the IAEA-NEA, if all conventional resources are considered, there are about 14.4 million tonnes of uranium available, which is over 200 years' supply at today's rate of consumption. But these estimates still omit what might be regarded as unconventional resources, such as phosphate deposits (22 Mt) and seawater (up to 4000 Mt), which would apparently cost two to six times the present market price to extract. Reprocessing of spent fuel from conventional light water reactors is also considered to utilise present resources more efficiently, by a factor of about 1.2.

All of this only relates to uranium-235. This can be used to fuel a breeder reactor that converts the uranium-238 into plutonium-239, which can also be used in a fission reactor. The use of the fast breeder reactor could thus increase the utilisation of uranium by at least a factor of 60 if necessary.

#### **Thorium**

Thorium, as well as uranium, can be used as a nuclear fuel. It is about three times as abundant in the earth's crust as uranium, and all of the mined thorium is potentially useable in a reactor. Total estimated extractable reserves of thorium are about 1.2 Mt.

Although not fissile itself, thorium-232 (Th-232) will absorb slow neutrons to produce uranium-233 (U-233), which is fissile. Thus like uranium-238 (U-238) it is fertile.

In fact U-233 has often been considered to be better than uranium-235 and plutonium-239 in one particular respect because of its higher neutron yield per neutron absorbed. Thus a breeding cycle similar to, but more efficient than, one making use of U-238 and plutonium (in slow-neutron reactors) could be established. The Th-232 absorbs a neutron to become Th-233, normally decaying to protactinium-233 and then U-233. The U-233, which can be reasonably easily separated from thorium, could then be used in another reactor. The general consensus appears to be that much development work is still required before the thorium fuel cycle can be commercialised, and the effort required seems unlikely while (or where) abundant uranium is available. But nevertheless, the thorium fuel cycle, with its potential for breeding fuel without the need for fast-neutron reactors, holds considerable long-term potential, and will be a key factor in making full use of the potential of nuclear energy.

The world's annual production of nuclear energy presently amounts to about 8 PWh, but only ca 35% of the energy is used for the production of electricity. The rest, in the form of steam and warm water, is essentially wasted. There are presently 440 operational reactors in the world (November 2003) in 31 different countries. In 10 countries more than 40% of the electricity is coming from nuclear reactors. Following a rapid development 1960-1985, mainly in Europe, Japan and USA, most of the new installations are now in Asia. Most available nuclear reactors are using uranium as fuel with the fission energy mainly coming from the U235 isotope. The magnitude of available terrestrial resources of uranium which can be obtained for a cost less than \$260/kg U (Uranium) amounts to some 17 Mt having an approximate energy content of 2750 PWh or equivalent to about 400Gt coal. (The amount of generated electricity in present reactors is about a third of this) This is less than the estimated coal reserves but larger than the oil reserves. However, the total amount of uranium is likely to be much larger as we here only have included uranium ore costing less than \$260/kg, neither have we included uranium in sea water. In addition the reserves of thorium, which also can be used as nuclear fuel, is about twice as large as that of uranium, Bodansky, 2004.

However, the most important issue is that nuclear fuel can be used more efficiently by adopting a breeder reactor fuel cycle. With a breeder reactor the amount of energy yield of uranium increases greatly. If the increase is a factor of 50 (which appear to be a realistic figure) than the amount of energy will increase correspondingly and so will the value of uranium for exploration. We may therefore assume that for the foreseeable future that available fissile energy in uranium and thorium would be sufficient for the expected energy requirements.

Although, there have been technical problems with present breeder reactors there are indications that new attempts are on the way (The Japanese supreme court recently (20 May 2005) gave approval for the reopening of the Monju fast breeder reactor). *Nevertheless, such problems must be put in a context where they are compared with anticipated negative consequences in producing energy from fossil fuel or from environmental damage due to excessive exploration of regenerative energy sources.*

In principle nuclear energy can provide energy for the world but major research efforts are needed to develop new types of reactors providing higher security and more efficient use of uranium and thorium. Such systems are presently being pursued and should be strongly encouraged. Furthermore, these systems are planned to be combined with systems for the generation of hydrogen (using the thermal energy) as well as desalination plants (also using the thermal energy). Therefore, under present circumstances, it appears that the development of nuclear power is the most and probably the only realistic alternative if the world wishes to significantly reduce its dependency on fossil fuels. In the longer perspective fusion power is a possibility but presumably operational systems cannot be completed before the middle of the century.

Needless to say, it will be necessary to solve several technical problems in relation to security and storage of waste but we believe these problems are solvable in particular if we compare those with potential problems with other types of major energy installations. We leave the political problems outside of this study as these include considerations that are strongly subjective and cannot easily be evaluated. Furthermore, they may change for reasons that are not predictable.

## **6. 2 Fusion energy**

In the longer perspective the most promising approach towards solving the energy problems of the world is by using nuclear fusion. The basic fuel for fusion energy is deuterium and lithium, which are abundantly available practically everywhere on Earth. The “ash” for fusion burn is helium, which is not radioactive. The intermediate fuel (tritium) is produced from lithium in the mantle of the reactor. Following preparatory research over a longer period of time the so-called ITER project has been established (<http://www.iter.org/index.htm>). It is a joint project with the participation of EU, Canada, Japan, Russia, USA, China and South Korea under the auspices of IAEA. ITER will build an experimental, tokamak type reactor, which will serve as a prototype and a demonstration. It has recently been decided (June 2005) that it will be constructed at Cadarache in France. ITER has a time scale of 10 years and will at the end (2016) be able to produce 500 MW. Following a hopefully successful outcome the experience of ITER will be used for the building of the first operational fusion reactors. As there are several complex issues involved such as the longer-term stability of the high-temperature plasma it is probably not feasible to consider any operational fusion energy before 2050. However, given a successful outcome fusion power it is likely to solve the energy problems of the world.

## **7. CONCLUDING REMARKS**

Because of lack of investment in nuclear power and regenerative energy as well as inherent limitations in the latter, the strong dependence of fossil fuel is likely to remain for several decades. This combined with the need to raise energy production is expected to increase the concentration of carbon dioxide to approach a value twice that of the pre-industrial time towards the middle of the century. Such a high value is likely to give rise to irreversible changes in the climate of the Earth.

It seems that two major actions are needed and should be implemented with highest priority. These are carbon dioxide sequestration and increased investment in nuclear

power, preferably using fast breeder reactors. Energy savings and further development of regenerative energy systems will certainly contribute towards reducing the increase in the use fossil fuel but it will insufficient.

What then are the practical possibilities as seen from different time perspectives? We suggest a step-wise strategy along the following lines, which can be outlined as follows:

2005-2015: During this period the dependency on fossil fuel is not likely to be changed in any significant way. Ongoing development of regenerative energy (wind, solar, hydroelectricity, etc.) will increase but is not likely to increase its present relative small part of TPES. The only feasible alternative for the replacement of fossil fuel, it seems, is by nuclear energy (fission energy). Any major development is not being expected and ongoing installations is offset by the dismantling of installations elsewhere. However, there are recent signs that public attitude to nuclear energy (including that of some leading environmentalists) is becoming more positive in Europe and United States and this in combination of high energy prices may encourage new investment in nuclear energy.

2015-2030: An important strategic initiative would be a forceful research and development program on the use of fission energy through the use of new types of reactor presently being planned such as the IV generation of nuclear power stations (<http://gif.inel.gov/roadmap/>). These types of reactors can also provide a better treatment of waste such as transmutation of long-lived radioactive isotopes. The IV generation nuclear systems are also planned to be combined with systems for hydrogen generation, which could be a suitable replacement of petrol for the transport sector. The use of fossil fuel in the period until 2030 is expected to increase the concentration of CO<sub>2</sub> in the atmosphere to around 450 ppm. In view of the inertia of changing existing fossil based energy systems as well as the negative public view in many countries vis-à-vis nuclear energy this is probably unavoidable.

2030-2050: During this period it is to be expected that the supply of oil and gas will be inadequate leading to significant increase in cost and potentially serious economical problems. Production of oil from coal by the Fischer-Tropsch process is feasible but will require a doubling of the use of coal.

2050- and later: If the research and the ongoing development towards the practical use of fusion energy (as hopefully will be the result of the ITER-project) than we could after 2050 have running fusion energy systems. If that is to happen than we have a likely chance to solve the world's energy problem including the generation of hydrogen gas for the transport sector. If not it will be necessary to significantly increase the creation of energy systems based on fission power.

## REFERENCES

- Bartlett, A. A., 2004: Thoughts on long-term energy supplies: Scientist and the silent lie, *Physics Today* July 2004, 53- 55
- Bodansky, D., 2004: *Nuclear energy, Principles, Practices and Prospects*, Second Edition. 2004, 693 pp., Springer-Verlag, New York, LLC. ISBN 0-387-20778-3

Hill, R. C., 2002: Nuclear power as an energy source. *Science* vol. 298, issue 5598, 11553-1554

Key World Energy Statistics (2004) International Energy Agency (IEA)

Sailor, W. C. et al., 2000: A nuclear solution to climate change, *Science*, Volume 288, Issue 1177-1178

Weisz, P. B., 2004: Basic choices and constraints on long-term energy supplies. *Physics Today*, July 2004 47-52

