17
Saving Energy and Renewable Energy Through Crystal Technology

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17.1
Introduction

After the oil crisis, the Club of Rome [5] predicted in "Dynamics of Growth in a Finite World" a shortage of fossil energy resources and a severe energy crisis including armed conflicts for the end of the last century. It is realized now that this report was too pessimistic, but it contributed to start or enforce the "green" political initiatives and parties mainly in central European countries and in Japan. This green political influence, while being partially understandable, developed as a burden for the industries and therefore enhanced economic slowdown and recession. With respect to energy the green public and political influence caused a widespread concern about nuclear fission energy and nuclear waste so that in several countries the efficient fast-breeder reactors and even the conventional nuclear reactors were stopped or will be stopped in the foreseeable future. This is not understandable, neither from a technical nor from a safety point of view. Studies of the risks (deaths and health) of the energy sources have shown that nuclear fission energy is much safer with respect to mortality and health, by at least an order of magnitude, than oil and coal. There is a propagandistic overemphasis of the terrible accident of Chernobyl, whereas the daily accidents in connection with coal and oil mining, oil transport and utilization, and with gas explosions as well as the negative health effects of polluted air are ignored.

The combined effect of the limited resources of fossil energy and the political demand to reduce nuclear fission energy in certain countries will lead to a serious energy crisis in the next 30 years if there is not a timely and sufficient development of alternative and renewable energy sources in combination with energy saving and a revival of nuclear energy. This should compensate for the increasing worldwide demand of electricity of annually 2.6% as shown in Fig. 17.1, due to the growth of population and due to the increasing standard of living in large parts of the world, notably in the former communist states, in China, India, Africa, South America, and other developing countries.

The energy problem is interconnected with the *climate problem*, with global warming, which has become clear and internationally recognized especially after

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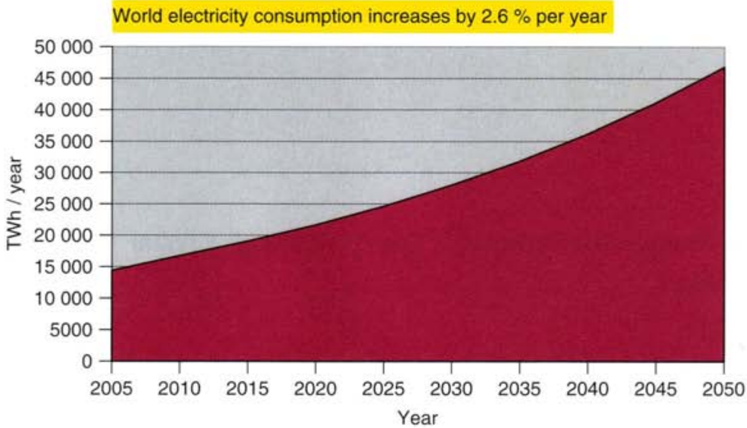


Fig. 17.1 The future world energy consumption, due to population growth and increasing standard of living, will show an annual increase of 2.6% and thus will double by the year 2040.

the report of the UN Intergovernmental Panel on Climate Change (IPCC) which published the first part of their conclusions (of a total of 4 parts) on February 2, 2007 in Paris.

The production of carbon dioxide by burning the fossil energy sources coal, oil and gas has to be reduced (or CO_2 has to be absorbed) in order to prevent an increase of catastrophic effects of the climate change such as the rising sea level and extreme weather situations like hurricanes, flooding, and droughts. The International Disasters Database shows a significant increase of hydrometeorological disasters since 1986 (see CRED website [3]). The regional differences of CO_2 emission per person are shown in Fig. 17.2. They clearly depend on the development stage of the area, on the transport characteristics of people and material, and whether electricity is produced from fossil primary energy sources. These aspects should be seriously considered in North America and Australia, for example, the USA could contribute by reducing electricity production of presently 70% from fossil resources, by increasing the gasoline price, and by introducing a CO_2 tax. However, one would expect an increased CO_2 production with future development of China, India and other less-developed countries along with the increasing standard of living of more than 4 billion people. The proposals of the Kyoto Protocol for reduction of the CO_2 generation demand a worldwide faster reduction of the share of fossil energy than the reduction forced by the limited resources lasting 40 to 60 years only. The coal reserves will last longer, but coal for producing electric energy should only be increased if the higher CO_2 output can be absorbed by storage in deep ground or deep sea, or by new technological processes, since the natural absorption of CO_2 by photosynthesis of trees and plants in general does not suffice. In any case, oil reserves should be kept as high-value base material to service the chemical and plastic industries for future generations.

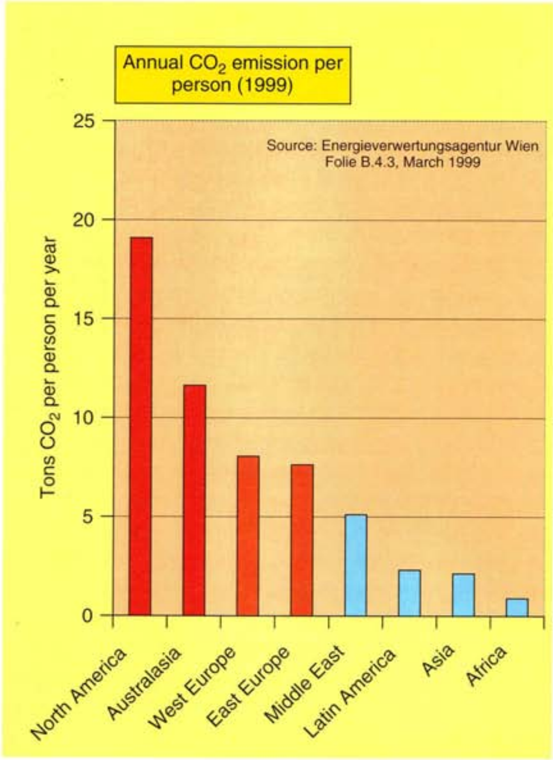


Fig. 17.2 Regional differences of the annual CO_2 production per person are very large. The less-developed countries have to increase CO_2 output parallel with their development, whereas USA and Australia should reduce CO_2 production.

According to the World Energy Outlook [15] of the IEA there are 1.6 billion people, of which more than 80% are in rural areas, without electricity. This problem could be solved by bio-energy or by photovoltaic solar energy (and corresponding investments) as discussed below.

In the following, the developments of the conventional energy sources and possibilities to save electrical energy by high-power, high-temperature electronics and by new illumination sources will be discussed along with the decisive role of crystal technology. High-temperature superconductivity (HTS) could have an enormous effect on energy transport, on energy storage, and on energy saving if the crystal/epilayer/materials problems for development of the required devices, cables and coils could be mastered. Then, the renewable energy sources will be treated where also crystal technology, including epitaxy technology, is the crucial factor for progress. Finally, the need for publicity, education, and funding for the multidisciplinary and complex field of crystal technology will be discussed.

17.2
Storage, Transport and Saving of Energy

The conventional forms of energy like coal, oil, and gas are high-density and condensed forms of energy, so that *storage* of fossil energy is not a major problem. However, the renewable wind energy and solar energy generate electric energy only at specific times for limited periods, and these periods do not, in general, coincide with the peak energy-consumption times. Thus, economic storage of electrical energy becomes a problem since conventional lead-based batteries and also novel batteries require too high an investment, besides their large weight and space requirements. In many countries the geographic structure allows excess electricity to be stored in water pump systems with reservoirs, which has to be further exploited. The energy storage by means of very high energy storage systems (up to 5 GWh) based on supercapacitors, superconducting magnetic energy storage (SMES), and using large flywheels on superconducting friction-free bearings are too expensive for most applications. Energy storage based on superconductors has to await the material development of the necessary HTS-magnet systems, especially the development of thin reliable HTS wires and coils, so that economic cooling by liquid nitrogen can be applied instead of expensive and complex helium cooling. Another possibility of energy storage is hydrogen, using first the hydrogen contained in natural gas and later the electric energy from the renewable energy sources directly for electrolysis, or efficient in-situ electrolytic solar cells or other hydrogen-producing technologies, for instance in high-temperature nuclear reactors of the fourth generation, are developed. However, other forms of energy storage should also be found, investigated and developed.

The *transport* of the high-density energy carriers like oil and gas is not problematic as long as the pipelines are not interrupted due to natural events or due to human interference (sabotage, fire, politics, war). The conventional transport of electricity is done with power lines and high-voltage alternating current (AC). This has relatively large losses that could be significantly reduced by changing to high-voltage direct-current (DC) power transmission. This will become economic when efficient AC–DC and DC–AC converters, fault-current limiters, and transformers are developed, for instance based on improved high-power devices with GaN and SiC and on high-temperature superconductivity discussed in the following.

After the initial rise of the highest superconducting temperature from 23 K to 30 K [2] and the discovery of *high-temperature superconductivity* (HTS) at 92 K, i.e. above the boiling point of liquid nitrogen and above the classical BCS theory, by Wu *et al.* [16], there was hope that HTS could have a large impact on storage, transport and especially on saving of energy. Unfortunately, the complex chemical and structural nature of the HTS compounds and their limited thermodynamic stability were not appropriately considered in the physics-dominated research, even reproducibility of solid-state physical experiments was in general not achieved in the hectic ten years following the promising HTS discovery so that the development of HTS theory was also hampered.

The lack of reproducibility in HTS solid-state physics is explained firstly by the fact that the processes of HTS crystal, epilayer and ceramic fabrication are not reproducible due to the complex HTS compounds and the numerous preparation parameters, and secondly because *sufficient characterization* of the samples was never done. (Sufficient characterization is the analysis of all those chemical and structural features of the sample that have an influence on the specific physical measurement, Scheel [7].) Thus, the contributions of HTS to the energy problem have to wait for a serious materials, crystal growth and epitaxy effort to master these delicate HTS compounds.

There are many forms of *saving energy*: everybody can contribute by improving the efficiency in using electric appliances, thermal insulation of buildings, in heating and air-conditioning and the application of heat pumps, in personal and material transport, etc. Here, we will show with a few examples how crystal technology can contribute to energy saving. After solving the growth and doping problems of GaN by the Akasaki group [1] and after the development of industrial GaN-based light-emitting diodes (LEDs) in 1993 by Nakamura of Nishia company [6] the incandescent and fluorescent lamps of typical 15 and 50% efficiency will be replaced by high-efficiency colored LEDs for traffic lights and successively by white LEDs for general illumination. Figure 17.3 compares the brightness and the lifetimes of incandescent lamps, fluorescent and the new energy-saving lamps with the very promising values of the LEDs. The latter undoubtedly will become the dominating light source when their efficiencies and lifetimes are further improved and their fabrication costs reduced by crystal technology. Worldwide, these new illumination sources will lead to energy savings corresponding to $>\$10^{12}$ per year. Just the replacement of the green, yellow and red traffic lights by LEDs of LPE- and MOCVD-grown compound semiconductors will allow worldwide energy savings of about \$1.3 billion and reduce annual greenhouse gas production by about 400 million tons. High-power, high-temperature electronics based on either GaN or SiC also allows tremendous savings of energy of more than $\$10^{12}$. In these latter cases the crystal technology is the main progress-determining factor.

17.3 World Energy Consumption and Conventional Energy Sources

The consumption of energy will increase dramatically during this century as is shown in Fig. 17.1. The main causes for this increase are the growing world population and the increasing standard of living in most of the Asian, African and South-American countries. In Fig. 17.4 are schematically shown the trends of conventional energy sources and the quite optimistic increase of renewable energy until the year 2050, a scenario proposed by Shell in 2001. In this diagram the relative absolute values for the year 2050 have been derived by multiplying the 2050 percentages of the original Shell scenario by a factor 2.5 corresponding to the increased energy consumption from Fig. 17.1. If the excessive use of *fossil*

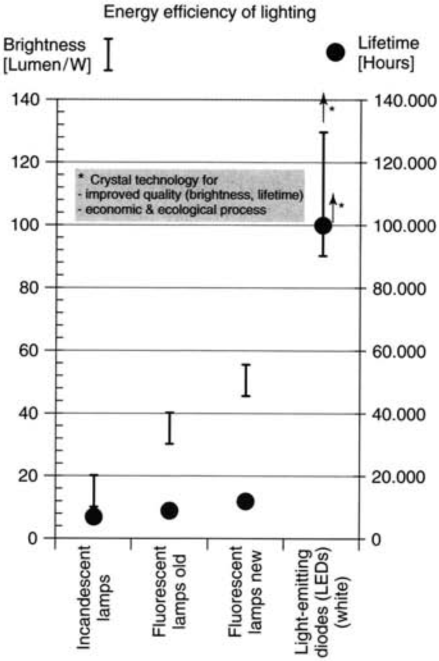


Fig. 17.3 The energy efficiency of lighting is shown and indicates that an enormous amount of energy can be saved by light-emitting diodes that at the same time have very long lifetimes. Even further improvements and cost reductions of LEDs are expected due to crystal technology, as is indicated by the arrows.

energy (thermal power stations, large cars, etc.) continues, there will be a more rapid reduction of this form of energy as a consequence of the limited oil resources.

Hydraulic energy will increase slightly, but of course has an inherent natural limit except for hydraulic storage of excess energy by means of pumping stations and water reservoirs. Also, sea waves and tide energy may be developed at certain coastal sites.

Nuclear fission energy could, in principle, be increased in all industrialized countries if there were not the green political efforts to even stop the nuclear energy due to misled concerns about safety and about storage of nuclear waste, the latter being not a technical but a purely political problem. Furthermore, there is no technological base for the concerns about nuclear energy, so that the important energy problem should not be left to politicians. Instead, it should be left to technocrats and energy managers. Furthermore, it is necessary to increase the fast-breeder technology and the high-temperature reactors, following the recommendations of the "Generation IV International Forum (GIF)" and the proper safety measures, since these reactors of the fourth generation have a significantly higher overall

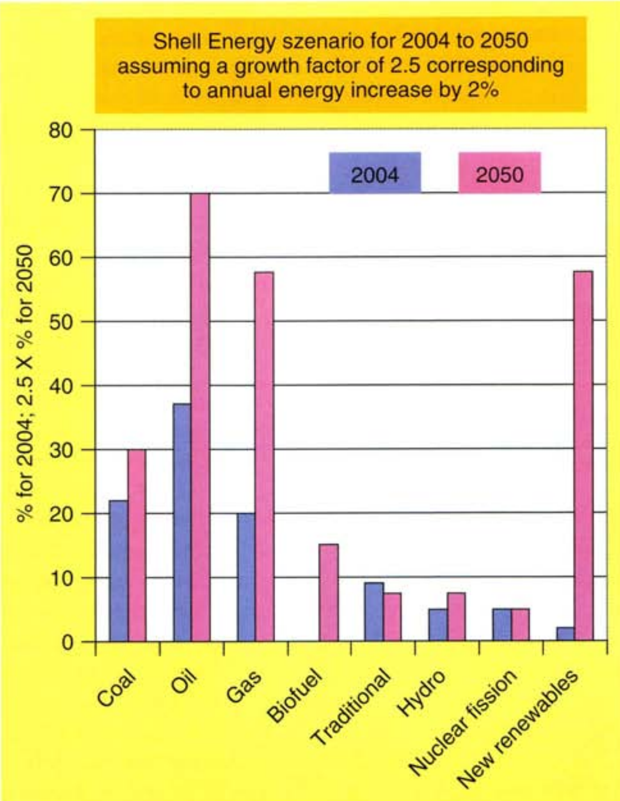


Fig. 17.4 From the scenario of SHELL (2001), the relative contributions to the total energy in the years 2004 (1x %) and 2050 (2.5x %) are shown taking into account the 2.5-fold energy consumption in the year 2050, as shown in Fig. 17.1. The steep increase of renewable energy seems unrealistic and probably has to be replaced by steeply increased nuclear fission energy until nuclear fusion is developed.

efficiency than conventional water-moderated reactors, use less resources, produce much less radioactive waste, and present a reduced proliferation risk of isotopes for nuclear bombs. Furthermore, the *ultrahigh temperature reactor* allows the production of hydrogen that is needed for the fuel-cell-driven cars allowing personal transport without CO_2 production.

From this discussion it follows that, unless nuclear power is drastically increased, mankind will face a severe energy crisis in this century. An example is demonstrated with Switzerland where around 2020 two nuclear power stations are planned to be switched off as demonstrated in Fig. 17.5. In view of the increasing consumption of electricity there will arise a problem of which the solution is not in sight. Switzerland missed the chance of a timely replacement of the nuclear power stations because of the political pressure of opponents of nuclear fission

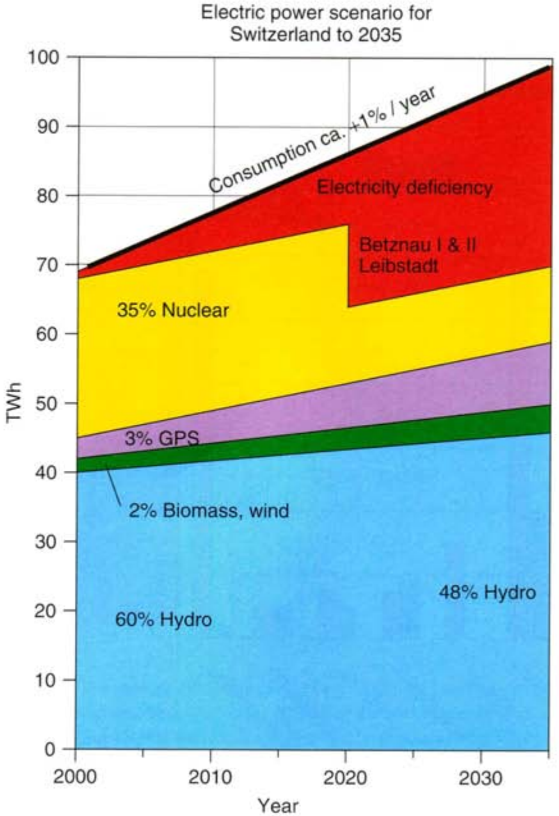


Fig. 17.5 The energy scenario for Switzerland that will have a problem when around the year 2020 two nuclear power stations are planned to be switched off.

energy and the malinformed public. Not only in Switzerland but worldwide it seems doubtful, if not impossible, that energy-saving efforts in combination with novel energy sources will be developed fast enough to fill the energy gap and to prevent armed conflicts for the last resources that started in 2003 with the Iraq war.

17.4
Future Energy Sources

The optimistic development of the major new energy sources is shown in Fig. 17.4. Presently, there is great interest in *wind energy*, which could become economic in areas with sufficient frequent wind if the oil price were to be increased, and if efficient electricity storage could be developed. Various forms of energy from *biomass* are in development and will contribute to the share of renewable energy, but at present a large impact is not in sight due to the surface-area requirement and the competition with food production for the growing world population. However, in rural areas local biogas production, gas motors and electricity generators will increasingly provide heating, air-conditioning and electric power.

Geothermal energy looks quite straightforward and could be developed in numerous areas where the rock structure and the temperature profile are suitable, especially near volcanic regions. However, a pilot project near Bale, Switzerland caused earthquakes of magnitude 3.4, so that people became afraid, with the consequence that the project was temporarily interrupted. Hopefully, ways to prevent earthquakes can be found or the project shifted to less-populated areas so that this promising quasipermanent source of energy can be exploited. In geologically favorable areas 10 to 30% of electricity demand could be provided by economic geothermal energy.

Solar thermal energy is widely used in countries of sufficient sunshine for heating water, for air-conditioning, and for evaporating water for drying and for salt production.

Photovoltaic solar cells are in development using a large variety of materials and of technologies, but a real breakthrough has not yet been achieved, see Surek [14]. Single-crystalline and polycrystalline silicon have the major share with about 87%, leading to a temporary shortage of economic solar-grade silicon, and the remaining fraction consists of compound semiconductors. According to a 1998 estimate by the German Fraunhofer Institute for Solar Energy Systems, solar PV power will reach the 1% level of total electric energy, at 30% annual growth, only in the year 2040.

The company Spectrolab in California and several research laboratories have reported efficiencies of over 40%, and theoretically over 45% could be achieved at maximum utilization of the full wavelength spectrum of solar radiation by means of multilayer/tandem structures of compound semiconductors and concentration of solar light by mirrors or lenses by factors of 100 to 1000. As a consequence of this concentration approach only very small PV cells are required so that their price is not so critical.

The minimum required efficiency for solar cells, to become economic for energy generation, depends on the oil price and should be at least 20%. In Fig. 17.6 the efficiencies of various research solar cells at the beginning of their life are shown: amorphous silicon has, at the beginning of its life, less than 10% and is decreasing with time, and crystallinity and crystalline perfection of silicon increases the efficiency to single-crystalline silicon, which marginally passes the 20% level. In view of the generally observed degradation there is the question whether Si-based solar cells will be used in large-scale power stations for generation of electricity not only for the low efficiency but also for the area requirement. Low-cost Si PV cells will be widely used for architecture (roofs, etc.) and for economic reasons in remote villages and homes, in combination with batteries, especially in less-developed countries, for instance to provide electricity to the 1.3 billion people in rural areas.

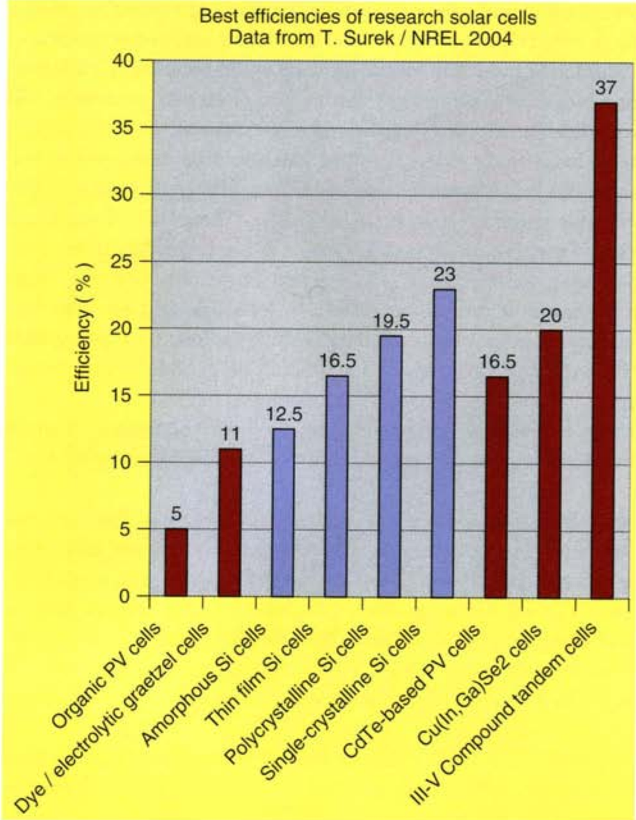


Fig. 17.6 Efficiencies of silicon-based research solar cells (blue) reach 23%, whereas efficiencies of >36% can be achieved in III-V compound tandem cells with concentrators. Only for solar-cell modules with >20% efficiency can one hope for economic large-scale electricity production.

The urgent development of mass-production technology for highest-efficiency PV cells and the optimized concentration methods are needed in order to increase the share of solar energy in total energy consumption. For a specific photovoltaic cell structure there can be only one optimum or a combination of two optimum epitaxial technologies for economical and ecological mass production, as discussed by Scheel [12]. Thus, the progress in solar-electric energy depends clearly on advances in industrial crystal, epilayer and multilayer fabrication and again in economic energy storage.

Nuclear fusion energy is the great hope for the future, and tremendous efforts were and are being spent to demonstrate and to achieve breakeven for this type of energy, especially for the magnetic inclusion of the high-temperature plasma

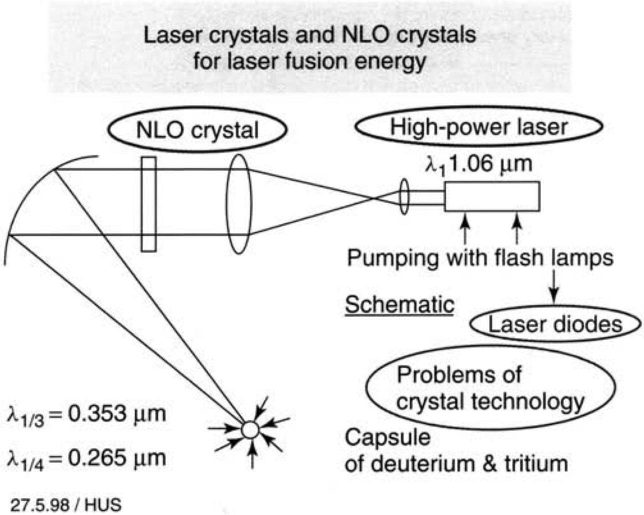
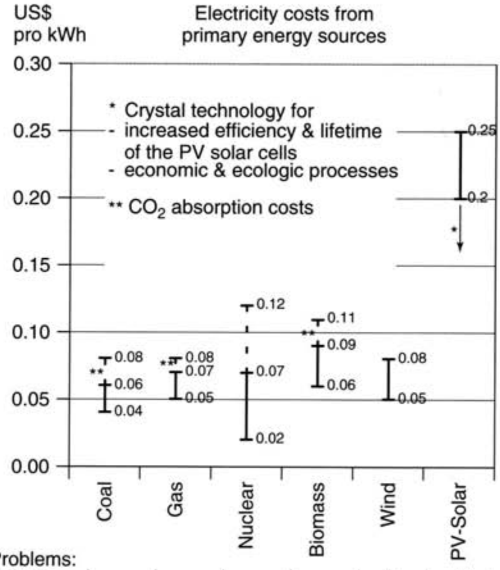


Fig. 17.7 The principle of laser-fusion energy is shown where the laser crystal is pumped by laser-diode arrays and where the frequency of the infrared radiation from the high-power laser crystal is multiplied by passing through the nonlinear optical crystal. The essential role of crystal technology for the high-power laser crystals, for the radiation-resistant nonlinear-optical crystals, and for the laser-diode arrays is indicated.

(TOKAMAK). However, this has to await the solution of the most severe material problem, to find long-lasting materials for the first and second wall around the plasma. Only this will allow energy generation by the TOKAMAK technology. The alternative is laser fusion that was demonstrated with glass lasers and large nonlinear-optic (NLO) crystals, so far KDP, for frequency multiplication, to achieve high-power UV pulses. The principle of future laser fusion is shown in Fig. 17.7. For continuous laser-fusion energy the development of highest-power laser crystals, with reduced thermal and surface degradation problems, of economic high-power laser diode arrays for pumping the lasers, and of improved large NLO crystals of excellent radiation hardness is required: These are solvable yet difficult problems for crystal-growth technology, for instance with special garnet- or apatite-type laser crystals and with CLBO or other NLO borate crystals.

17.5
Costs and Risks of Conventional and of Future Energy Sources

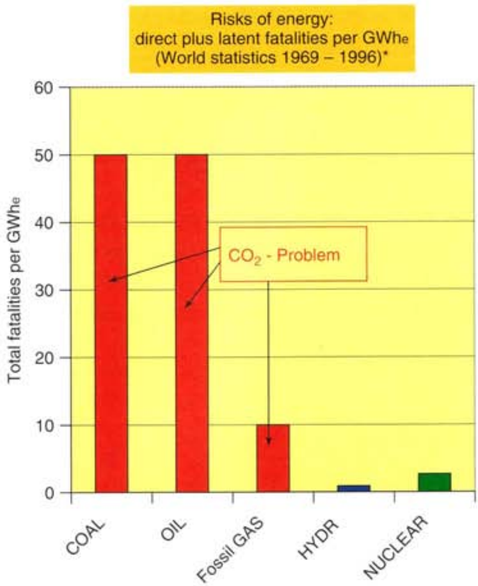
The utilization of the various forms of energy should be based on technological and economic factors taking into account ecological and environmental considerations. The estimated electricity production costs for the conventional and the new energy sources are shown in Fig. 17.8. Ideally, the role of politics ought to be limited to ensure low risks for workers in the energy field and for the population, to establish



Problems:	Coal	Gas	Nuclear	Biomass	Wind	PV-Solar
Storage	-	-	-	-	!!!	!!!
CO_2	!!!!	!!	-	±!	-	-
Risk	!!!!	!!	(!)	!	!	!

Fig. 17.8 The cost of electricity from renewable energy is still higher than present electricity cost so that significant technological improvements including crystal technology for the new energy sources are required. Also, the CO_2/climate and the energy-storage problems and the risks for the energy sources are indicated.

rules for the environment and the climate control, and to support the start-up of future energy sources in order to prevent a crisis due to energy shortage. The risk of nuclear power is, in general, overestimated as follows from the discussion of Shepherd and Shepherd [13]. Nuclear power is needed and has to be increased as discussed above, so that it would be quite harmful if it were to be reduced or even stopped. In the period 1976 to 1984 several studies on the risks of energy sources from Canadian and Swiss institutions were published, see Scheel [11]. A more recent study of energy-related accidents was done by Hirschberg *et al.* [4] and their mortality data, normalized to 1000 Megawatt electricity per year, is shown in Fig. 17.9. Coal and oil have by far the largest risk from exploration through transport to utilization, which is only rarely mentioned in the mass media. In contrast, hydraulic, fossil gas and nuclear power are connected with comparably small risks. Therefore, it is necessary to inform politicians and the general population about these statistical analyses of ministries and of insurance companies, and perhaps to initiate new unbiased risk studies.



* Data from "Severe accidents in the energy sector" 1st Ed., S. Hirschberg, G. Spiekermann and R. Dones, PSI Bericht Nr. 98-16, ISSN 1019-0643, Nov. 1998.

Fig. 17.9 The risks of the various energy sources expressed as number of annual casualties per GWh electricity are shown [4].

17.6 Crystal Technology and its Role for Energy

The various contributions of crystal-growth technology, CT, to the energy problem discussed above are summarized in Table 17.1. For energy-saving lighting the development of highest efficiency LEDs based on GaN and its solid solutions with AlN and InN is hampered by the nonavailability of GaN and solid-solution substrates. These would allow the preparation of epilayers and multilayers with reduced structural defects due to the very low misfit and very similar thermal expansion coefficients. Depending on the required layer structures even epitaxial growth near thermodynamic equilibrium by liquid phase epitaxy (LPE) could be considered, which would yield extremely flat surfaces and interfaces and very low dislocation densities (Scheel [10] Chapter 28, Scheel [12] Chapters 1 and 7). Similarly, epitaxial layers of improved structural perfection could increase the performance of power devices based on SiC and GaN where the harmful pipe defects, which lead to electrical breakthrough, can be overgrown by LPE.

Material problems in general and crystal-technology problems in specific areas will have to be solved if economic energy storage and energy transport are to be achieved. The role and problems of high-temperature superconductors have been

Table 17.1 Problems of crystal and epitaxy technology and of material technology for sustainable energy (Examples).

Energy saving

- White light-emitting diodes (GaN solid solutions) for general illumination/interior architecture and for traffic lights.
- High-power devices (GaN, SiC transistors, thyristors, etc.) for energy technology.
- High-temperature superconductors HTS for electric energy transport.
- HTS for motors, generators, current limiters, transformers, MHD ships, etc.

Energy storage

- Material for economic high-power batteries.
- Material for high-density hydrogen storage.
- HTS for flywheel or superconducting magnetic energy storage (SMES) of electrical energy.

Renewable energy sources

- Mass production of highest-efficiency (>36%) photovoltaic solar cell modules for various concentrator principles (lenses, mirrors, etc.) for power plants and for roofs/architecture.
- High-efficiency silicon and CIGS solar cell modules (~20%) on low-cost substrates for localized energy consumption (roofs, architecture in general).
- Photovoltaic solar cells for direct hydrogen production by electrolysis.
- Efficient thermophotovoltaic devices, thermoelectric devices.
- Corrosion-resistant metal-cooling system for fast-breeder fission reactors.
- Novel high-power laser crystals and radiation-resistant nonlinear-optic crystals for laser-fusion energy (and for future ultraintegrated microelectronic/UV-lithography).
- Economic laser-diode arrays of long lifetime for pumping the laser for laser-fusion energy.
- Materials for the first and second walls in TOKAMAK nuclear fusion technology.

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discussed above, and further the material problems for high-power batteries and for hydrogen storage need to be mentioned.

It is not widely recognized that crystal technology is a major factor for progress in renewable photovoltaic energy and especially in the future hope of nuclear fusion energy. A variety of materials and of preparation methods are applied for industrial production of photovoltaic solar cells, whereas in principle there can be only *one optimum material* (or material combination) and only *one optimum fabrication technology* for a specific application of solar cells if all factors like thermodynamics, economics, energy and resources consumption, ecology are considered [10].

A serious contribution of CT is more easily demanded than fulfilled because there is *no education for this field*, which is multidisciplinary and complex [8, 9, 11], and most crystal growers are specialized with respect to technology and material thus limiting crossfertilization. *Education* in the technology of crystal and epilayer fabrication is urgently required: most companies would hire engineers and scientists of this area if they were available: The estimate is more than 400 specialists per year. The first difficulty is the multidisciplinary nature of CT: Chemistry and chemical engineering, materials science and engineering, thermodynamics, mechanics including hydrodynamics, applied crystallography, solid-state physics and surface physics, statistical mechanics, and electrical engineering. This requires the study of the basics of most of these disciplines followed by a 2-year specialized course in crystal technology in combination with experimental work and industry visits and practice. The second difficulty is the structure of the universities with their specialized departments and the difficulty to introduce a novel multidisciplinary course.

Education of crystal-growth scientists and engineers would not only allow them to derive the *single optimum technology* for the production of a specific crystal or epilayer, but it would also lead to enormous savings of R&D and production expenses, to accelerated developments in the energy problem, and it would save energy!

17.7
Future Technologies for Mankind

The technological and scientific developments in the past 150 years and especially the electronic/communications revolution in the past 50 years are presenting mankind with a modern world that requires novel approaches to education, to communication, to work, and that also raises sociological, economic and environmental changes and problems. The advances in medicine prolong average life, so that the resulting growth of world population will lead to limited supplies of food and of energy. The main technologies contributing to the future of mankind are biotechnology for food and health, and crystal technology for saving energy and renewable energy and contribution to the CO_2/climate problem, see Fig. 17.10. Advances in the fashionable nanotechnology including microelectronics and optoelectronics are desirable and are also interesting research areas, but do not have the crucial impact and urgency of the food, health, energy and climate problems. In conclusion one may state that the technology of crystal and epilayer fabrication has been somewhat neglected in all aspects, with education, funding, and recognition. This has to change soon in view of the crucial importance of CT for energy, for the future of mankind.

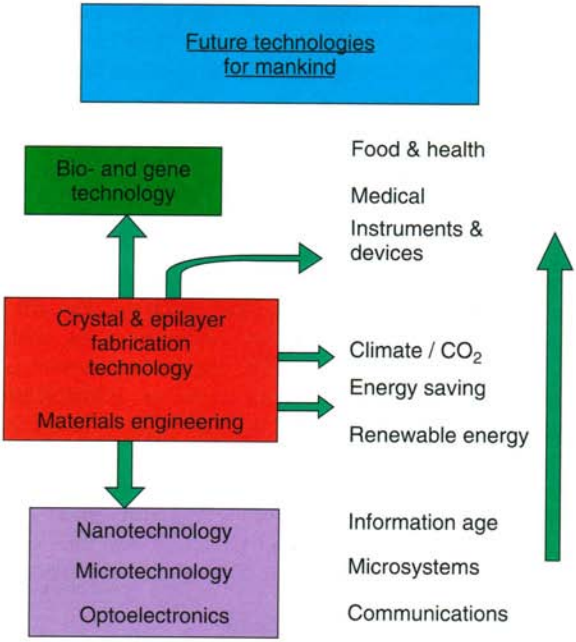

Fig. 17.10 The relative importance of the technologies for the future of mankind are schematically shown, the large arrow indicating the increasing importance from bottom to top.

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