Re-Examining the Future of Power Generation

To the Editor:

Please allow me to make a comment on the article by B.L. Eyre and J.R. Matthews on "Materials for the Power Industry," published in the July 2001 issue of *MRS Bulletin* [p. 547; www.mrs.org/publications/bulletin/21stcen/]. The authors deal with the very important issue of energy supply and sustainable growth for humankind in the 21st century. I got the impression that their article was somehow missing the strategic top-to-bottom approach which is necessary for such an issue. The authors think furthermore that developing countries need (at least initially) cheap solutions, rather than sophisticated ones. In a world of global communication, where everybody knows the state of the art, and in times where we realize that we are all sitting in the same "Spaceship Earth," this sounds like political discrimination. Developing countries, in my opinion, need state-of-the-art technical solutions as rapidly as possible, in order to prevent unnecessary pollution and tearing-up of the planet's resources.

The authors tie global warming in a simplistic way to CO_2 production. The physical factors influencing the earth's surface temperature are, however, manifold, and CO_2 concentration is only a minor contributor among them. To properly assess the problem of global warming, if ever there is one, we need a quantitative balance of the energy flows to and from the earth's surface. The earth receives about 95% of its relevant energy input from the sun, at a rate of ~1 kW/m^2 on vertical solar incidence. This energy has a short-wave blackbody-radiation spectrum, peaking at 500-nm wavelength (corresponding to a radiator temperature of about 6000 K). If the surface temperature of the earth is to remain at steady state, the *total* of the received and produced energy on earth must be radiated out to space. Part of the received solar energy is directly reflected back to space by the earth's surface "whiteness" (albedo) or by the clouds. This direct reflection occurs almost unhindered because the earth atmosphere is not absorbing significant parts of the 6000 K blackbody radiation. The remaining part of the solar energy is absorbed and converted to long-wave infrared radiation, peaking at 10-μm wavelength (corresponding to a radiator temperature of about 300 K). The escape of the 300 K radiation from the earth's surface is partially impeded by absorbing components in the earth atmosphere (greenhouse gases, greenhouse effect).

CO_2 has two relatively narrow spectral absorption bands in the thermal infrared, at 4.3-μm and at 13.9-μm wavelength, respectively. Between these bands, there is a large atmospheric window extending from ~7-μm to ~12-μm wavelength, through which the 300 K IR radiation of the earth's surface normally escapes into the 3 K cold space. The CO_2 concentration in the atmosphere is such that both spectral bands are already largely saturated under natural conditions, and the human-made increase in CO_2 concentration does only show up as a second-order effect (small enlargement of the spectral bands). CO_2 does not significantly close the atmospheric IR window. The by far most important greenhouse gas on our planet is water vapor, which is the only one able to close a significant part of the IR window.

The human-made contribution to the atmospheric CO_2 is estimated to amount to ~30% of the actual total concentration, as a consequence of our fossil-fuel burning. The total CO_2 concentration is actually increasing at a rate of ~1 ppm per year. It is also known that most of our planet's green plants are growing faster with higher CO_2, and the increase of the atmospheric CO_2 is certainly one of the reasons for the agricultural productivity increase during the last century. A somewhat higher CO_2 concentration could thus ultimately be a benefit for humankind and earth at short and medium terms. *In every case, we all agree that at long term, the CO_2 concentration in the earth atmosphere must be stabilized at an appropriate level*.

Stabilization of CO_2 cannot occur with chemical means, as the authors of the paper claim, because this would need a change in the global acid-base equilibrium of the planet. CO_2 cannot be hidden away underneath the earth surface either. The only reasonable way to eliminate CO_2 is through its decomposition into carbon and oxygen, or equivalent (e.g., through its fixation by photosynthesis). This implies putting carbon back to fossil reserve and oxygen back into the atmosphere again. Photosynthesis is, by the way, not only performed by woodland, but also by all kinds of green plants (grass, cultures) and algae (oceans). If the primary product of the photosynthetic activity (organic matter, wood) is not used up by people, animals, or microorganisms (who transform it back to CO_2), it is constituting a reserve, becoming eventually carbon or fossil hydrocarbon. CO_2 must, therefore, not be considered as an evil in itself; it is a mere vector of energy, which needs to be mastered and stabilized at long term.

Nuclear power has certainly the potential to replace a large amount of our fossil-energy consumption on a medium to long term, even if it is "fossil energy" too, in the sense that it is tied to a nonrenewable resource. The authors of the article account for nuclear energy, but do not mention the principal social problems connected with today's nuclear fission reactors, which are (1) potential sources of fissile materials for nuclear weapons (proliferation), and (2) producers of long-lived radioactive waste; both major threats to humankind. Furthermore, the plutonium, which is becoming available from the disarmament of nuclear weaponry, constitutes another threat to humankind and must in consequence be used up somehow, to take it out of the reach of criminal activities. This is why the exploitation of nuclear fission power has actually to be continued; mixed-oxide uranium/plutonium reactor fuel is a good way to get rid of the surplus weapon plutonium.

Personally, I do not believe in the success of nuclear fusion reactors based on the actually known laws of physics. The necessary temperatures for the thermonuclear fusion conditions (several millions of Kelvin) are too high to be reached and kept in a small area with a reasonable effort, due to the Stephan–Boltzmann radiation law, which states that energy radiation loss goes up with the fourth power of temperature.

The future of nuclear energy seems to me rather in accelerator-driven fission (spallation) reactors. This technology uses a beam of 1-GeV protons to produce an intense flux of rapid neutrons by spallation of a heavy-atom target. The abundant rapid neutrons are able to induce fission in nuclei with odd and even mass; therefore, the abundantly occurring natural ^{238}U and ^{232}Th isotopes can be directly used as a fuel. The reactor, furthermore, does not contain a critical mass of fissionable material, and it can be switched off at any time by switching off the accelerator. Furthermore, no actinides and no long-lived radioactive fission isotopes are produced in the process, such that the problems of proliferation and of nuclear long-term waste no longer arise. The reactor of this type can furthermore be used to *incinerate the already existing nuclear fission waste*. The technology has been proven in principle, and its first industrial implementations could be available within 10–20 years. The problems to solve up to then are mainly twofold: (1) to build an energy-efficient 1-GeV proton accelerator (about 40% overall efficiency from the electrical grid to the beam is required), and (2) to find an industrially practicable reactor

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design, which implies heavy issues for materials research.

In the field of the renewable energy sources, humankind will progressively rely on increased volumes of installed silicon solar cells, windmills, co-generation, bio-fuel, and hydro- and thermoelectric power stations, which are all in fact available as industrial commodities now. The same holds for hydroelectric energy storage systems, as well as for batteries of the most various kinds. The economic use of the available energy sources will be a further consequence of a changed mindset. There is, certainly, still considerable potential for materials research in the development of efficient fuel cells for automotive applications. Of particular interest in this respect are converters of carbon-containing fuels, such as the methanol–water/CO_2–hydrogen converter; the generated hydrogen can be used to subsequently drive a hydrogen-oxygen fuel cell whose technology is well known and working. Carbon-based chemical fuels are in any case a better way to store hydrogen in a concentrated, safe, and light-weighted form for automotive applications than are heavy metals such as nickel alloys, or dangerous high-pressure bottles.

Edgar Müller

Response:

We thank Dr. Müller for his interest in and comments on our article. He raises a number of issues and criticisms that we will respond to.

First, our article is a brief overview of materials issues related to the future development of power-generation. We summarized our opinions regarding strategy from a top-down viewpoint. To attempt a more detailed analysis would have detracted from the main focus of this article.

Second, regarding CO_2, Dr. Müller indicates that we have overstated its relative importance to global warming. However, we are not convinced by his interpretation of the physical processes. Calculations show (see the "Climate Change 2001" report from IPCC) that of the greenhouse gases, CO_2 makes the largest contribution to radiative forcing of the climate system in the year 2000 relative to 1750. In carrying out such calculations, it is necessary to take into account Doppler broadening and other molecular effects in widening the absorption bands, particularly over the longer wavelengths. The physics behind this is well documented in the literature. Thus, while other greenhouse gases have larger specific effects (e.g., methane and nitrous oxide), CO_2 is an important greenhouse gas not least because the anthropogenic fraction is so large relative to the other gases. We of course acknowledge the importance of water vapor in being responsible for a major feedback in accounting for the large warming predicted by climate-change models in response to an increase in CO_2. The effect comes about because the increase in temperature of the atmosphere increases its water-holding capacity. Thus the water-vapor effect is a direct result of the global-warming effect, and calculations show that its feedback approximately doubles the warming from what it would be for fixed water vapor.

Third, we only briefly touched on carbon sequestration since there did not appear to be major materials issues. However, we question Dr. Müller's rejection of chemical methods and deep underground storage. The fact is that work is being carried out on these methods in a number of countries as well as on photosynthesis. All of the methods have potential difficulties.

Fourth, on fission nuclear power, while it was not appropriate in our article to review in detail all of the sociological factors, we did refer to the main issues of safety, waste management, proliferation, and economics. We maintain our view that nuclear power has an important role to play in meeting the changing energy needs of the 21st century, and we highlighted some of the key technological issues.

Fifth, Dr. Müller is incorrect in his dismissal of fusion on the basis of the known laws of physics. Radiation losses are not the key issue for reaching the conditions for fusion in the plasma. The main energy-loss problem is related to impurities in the plasma that leak to the first wall. Technological solutions to this problem are being developed, and the current generation of fusion machines have approached the critical conditions for fusion burn, where the energy output exceeds the energy input. The key issue for fusion is the economic viability of the engineering of power-generation systems, and here, solutions to materials problems will play a key role.

Sixth, with regard to accelerator-driven spallation systems, these are at a conceptual stage and the economics are a long way from being confirmed. Their impact on dealing with nuclear waste through transmutation is limited to the transuranic actinides.

Last, on renewable energy technologies, with the exception of hydro power, they cannot yet be considered to be industrial commodities. The so-called new renewables contribute a very small fraction of the current global energy demand (<0.2%). While it is necessary to continue to develop the technology, it is important to also be realistic about their contribution and the significant technology barriers still to be overcome. As with all energy technologies, including generation and end-use efficiency, they have a role within an overall energy mix.

In summary, our article is aimed at presenting a balanced overview of materials issues relating to power-generation systems.

B.L. Eyre
University of Oxford
and
J.R. Matthews
University College London

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