Biomimetic technologies may help to shift to a more sustainable energy system

On photosynthesis and polar bears

As opposed to humankind, plants and animals rely completely on one kind of renewable energy: the sun's solar radiation. Biomimetic concepts mimic nature's energy system and may thus contribute to sustainability.

Von Christian Pade

The current anthropogenic system of energy generation, conversion, transport, and usage is, viewed on a global perspective, not at all a sustainable one. To a very large extent, it is based on the burning of fossil fuels such as coal, oil, and gas or wood and – to a much smaller extent – on the use of radioactive matter in nuclear power plants.

First of all, these modes of energy generation cause a number of detrimental effects to the environment, ranging from climate change to toxic nuclear radiation. Secondly, there are, less obvious but equally severe, economic effects caused by the conventional energy system. The latest turbulence in the markets has shown how vulnerable our economic system is to the availability and price of oil and gas – not mentioning the political disruptions, such as in the Russian-Ukrainian conflict on gas in the winter of 2005/2006. Last but not least, there are a number of adverse social effects such as migration induced by the unequal access to energy resources within and among different regions in the world.

The challenge of shifting to a sustainable energy system

In response to all of the above-mentioned negative effects of our current unsustainable energy system, strategies to change this system are being developed. Although there is still an ongoing, heated debate about which concrete measures are to be taken now and in the future, consensus seems to have already been reached on the fact that technological innovation must be at least one of the cards played in the energy game. For this reason, global measures have already been taken to foster the development of so-called renewable energy technologies. The main options in this context are energy technologies based on the use of water, wind, and solar power. Additionally, ways and technologies to use energy more efficiently are being investigated. In both instances, renewable energy technologies and energy efficiency, biomimetic concepts can play an important role, as will be shown in the following paragraphs (1).

Nature as a model for sustainable energy

In general, it seems somehow self-evident that nature can give at least some hints on how to generate, convert, transport, and use energy in a more sustainable manner. For billions of years, organisms have successfully managed to get the energy they need for their existence: for material build-up, for mobility, for reproduction, and the like. The source of energy for nearly the entire biosphere on Earth is the sun. Each year, the energy of 10^{24} Joule reaches the planet's surface through solar radiation. This is three orders of magnitude more than what is projected for the future global anthropogenic energy demand of 10^{21} Joule (Moore 2005).

Auto-phototrophic organisms like plants, algae, and some bacteria directly convert solar radiation into chemically-bound energy by building up energy-rich substances such as carbohydrates and fats, thus biomass, from energy-poor substances such as carbon dioxide and water through photosynthesis. Heterotrophic organisms like most bacteria, animals, and humans convert this energy-rich biomass into less energy-rich forms using the excess energy for their existence and survival. In the end, all biomass is again converted into energy-poor substances and the material cycle starts again – only being fuelled by the sun's solar radiation. Therefore, viewed in categories of sustainability management, the natural energy system may be considered, at least environmentally, as sustainable.

Biomimetic approaches in the energy domain

For this reason, it is not surprising that researchers in the field of biomimetics seek to mimic nature's energy system in one way or another (for a general overview, see Tributsch 2004). In this respect, the entire potential of bio-inspired energy concepts becomes only apparent if an integrated and holistic view is applied. That is to say, energy-related issues do not only refer to the question of energy generation from whatever primary source. Rather, energy conversion, transport, and usage are all of equal importance. In each of these fields, biomimetic approaches are at hand and are currently being developed further.

Examples include materials that mimic the pelt of polar bears, which converts solar radiation very effectively into heat (Tributsch et al. 1990). First biomimetical applications based ➜

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on the polar bear's pelt include transparent, thermally-insulated windows and passively heated textiles for outdoor clothing, which are currently under development (DBU 2006; Stegmaier et al. 2001 and personal communication with a member of the respective R&D institute). Other very popular examples for biomimetic approaches to a more efficient usage of energy include biologically-inspired surfaces or constructions that help to reduce flow resistance. Possible and realised applications are, for example, vessel and aeroplane hulls, swimsuits inspired by shark skin, or the outer form of an automobile inspired by the boxfish (Daimler/Chrysler 2007; Carlson et al 2006).

Biomimetic energy conversion

Although bio-inspired materials, structures, processes, and systems representing new ways of more efficient transport and use of energy are all of high importance in the context of sustainability, the following will focus on biomimetic technologies of energy generation and conversion (LaVan/Cha 2006). Two concepts have been chosen for a short discussion due to their high relevance in the current debate on renewable energy technologies: organic photovoltaics (OP) and artificial photosynthesis (AP).

Organic photovoltaics

The main functional principle of organic photovoltaics is identical to that of conventional photovoltaics: solar radiation is converted into electrical power (for an overview see Hepp et al. 2005). The main difference is with the materials used for conversion. Whereas conventional photovoltaic systems are mainly based on inorganic materials such as silicon (Si) and a variety of other semi-conducting materials such as gallium (Ga), indium (In), arsenic (As), cadmium (Cd), tellurium (Te), and selenium (Se), organic photovoltaic systems are based on organic materials.

OP systems involve a great variety of different organic materials including monomers, polymers, and fullerenes of very different types (Lane/Kafafi 2005). The advantages of OP systems over conventional Si-based systems are manifold (Goetzberger/Hoffmann 2005). First of all, OP systems are simpler and cheaper to manufacture, for their production processes do not need high temperatures, and roll-to-roll production, as in the case of newspaper printing, is possible. Second, some kinds of OP systems are capable of effectively using diffuse light so that they function on cloudy days, too. Third, OP systems allow for a greater variety of possible applications, since they are light weight and can, in principle, be integrated into various kinds of plastic foils, textiles, and even into windows. Concerning some of the mentioned advantages, thin-film solar cells based on inorganic materials show some of these characteristics, too (Morton 2006). However, contrary to OP systems, inorganic thin-film cells often involve the usage of toxic substances, and more energy is needed for production.

The main problems with organic photovoltaic systems are their low power conversion efficiency (PCE) and their relatively low long-term stability. Whereas conventional Si-based and thin-film solar cells reach power conversion efficiencies up to 20 percent and above and are stable over a period of 20 years and more, OP systems show efficiencies of only about 3 percent and are highly unstable (Lane/Kafafi 2005). However, progress made in recent years suggests that further research will probably lead to more efficient and stable OP systems that can compete with conventional photovoltaic systems.

One type of photovoltaic technology, which can be regarded a hybrid of inorganic and organic solar cells is the so-called dye sensitised solar cell (DSSC). It has been mainly invented and developed by M. Grätzel and his team, which is why this type of cell is often also called Grätzel cell (Grätzel 2003). It combines a nano-structured inorganic conductor, titanium dioxide, with an organic charge transfer dye, ruthenium-based organic complexes, and an organic solvent. DSSCs show all the advantages and, unfortunately, also disadvantages of OP systems as compared to conventional systems (Tulloch 2004; Tributsch 2004a). However, DSSCs have reached significantly higher PCE of 10 percent and above and show long-term stability similar to those of conventional systems (Grätzel 2006). For this reason, large scale production and long-term field testing of DSSCs have already started (ibid.).

Artificial photosynthesis

As its name implies, artificial photosynthesis (AP) seeks to mimic natural photosynthesis in a more direct way than OP systems do. As Pace (2005) puts it:

„Artificial photosynthesis (AP) is an umbrella term, embracing totally novel approaches to research into and development of technologies for non-polluting electricity generation, fuel production and carbon sequestration using solar energy. As the name implies, the inspiration is drawn from natural photosynthetic systems [...]." (Pace 2005)

In this definition, both aspects the mimicking of nature and the claim to sustainable technologies become apparent. Similarly to OP, AP is not a single approach but rather includes a large number of various concepts (Collings/Critchley 2005). Contrary to OP, AP approaches usually aim at the technical conversion of solar radiation into chemically-bound forms of energy. However, sometimes OP concepts are even included in AP (Collings/Critchley 2005 and the quoted definition above). Whereas considerable progress has been made in the field of OP, and first applications are expected to reach the market in the coming five to ten years, AP is currently under basic research only and functioning artificial photosynthetic systems will not be economically feasible within the next decades. Nevertheless, AP is already more than just science fiction. Researchers have learned a great deal about the highly complex structures and processes involved in natural photosynthetic systems and have been able to reconstruct at least parts of these systems (Wasielewski 2006; Alstrum-Acevedo et al. 2005; Gust et al. 2001). Therefore, artificial photosynthetic systems capable of converting sunlight into chemically-bound energy seem to be a realistic scenario at least in the long run.

Conclusion and outlook

The current anthropogenic energy system is by no means sustainable. Nature, on the contrary, has developed mechanisms of energy conversion, transport, and usage that can be judged as being sustainable. Therefore, biomimetic concepts in the energy domain have at least the potential of being more sustainable than conventional approaches. Organic photovoltaics and artificial photosynthesis are, among others, very promising concepts. However, to date almost no empirical data on the actual sustainability effects of current or future biomimetic energy technologies are available. Thus, more research on life-cycle aspects is needed.

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Annotations

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