AMBIO 2012, 41 (Supplement 2): 103–107
DOI 10.1007/s13280-012-0263-8

Overview: Capturing the Sun for Energy Production

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Abstract Solar energy has potential to provide a major part of our energy for our future, as heat, electricity, and fuels. Most solar technologies are still at the research and development stage, however. There is therefore a need for bold and enduring efforts in research, development and commercialization, including strategic legislative measures and infrastructure investments. This overview article serves as an introduction to the present Special Report, briefly outlining the potential, principles and possibilities as well as some of the challenges of solar energy conversion.

Keywords Solar energy · Photovoltaics · Solar fuels · Solar thermal energy

OUR ENERGY NEEDS TODAY AND IN THE FUTURE

Society is dependent on energy. Mankind consumes an astounding 140 000 TWh of energy per year (International Energy Agency 2010).[1] More than 80% of this is provided by fossil fuels: oil, coal, peat, and natural gas (Fig. 1). This is a major current and future concern: the resulting carbon dioxide emissions cause global warming; oil leakage and coal mining lead to additional pollution; the distribution of fossil resources lead to geopolitical problems; and in addition these fossil resources are not endless. To further amplify the problem, our energy consumption during the next decades is predicted to increase (RSAS Energy Committee 2010), in several estimates to about twice the current value in 2050 (Cook et al. 2010; International Energy Agency 2010; US Energy Information Administration 2011). Most of this increase will be in non-OEDC countries that need energy for societal development. The energy use and GDP per capita in a country are strongly correlated, as well as the GDP and well-being, measured by health parameters as, e.g., life expectancy (see www.gapminder.org). The poorest countries consume almost hundred times less energy per capita than, e.g., Japan and Sweden, and their citizens have a life expectancy of only 45–55 years instead of >80 years. Therefore, it is neither fair nor realistic to demand of these countries to stop increasing their energy consumption.

It is a challenge to find and develop alternative energy sources on a scale such that fossil fuels can be replaced or at least that their use will not increase. Most current alternatives have fundamental limitations of scale at around 10% of our current consumption or much less (hydro, onshore wind, wave, biomass) (Cook et al. 2010; US Energy Information Administration 2011). Also, the energy sector is an annual multi-trillion (10^{12}) dollar industry with large investments in infrastructure that causes resistance to changes. The metaphor of the very slow turn of an oil tanker is particularly appropriate in this case. However, infrastructure investments on a very large scale will be made anyway during the 40 years before 2050, as they have been during the last 40 years. For example, more than a thousand million homes will have to be built to replace old ones and make room for the increasing population. Also, doubling of the energy use means that half of the energy infrastructure needed in 2050 has not yet been built, whatever methods we use for production. Moreover, most of existing industry, vehicles etc. must be replaced during that time. The question is then what we choose to replace it with.

[1] Total primary energy supply (International Energy Agency 2010). 1 TWh (terawatt hour) = 1×10^9 kWh, where 1 kWh = 1 kilowatt of power during 1 h. 140 000 TWh/year = 16 TW (16×10^{12} W) of average primary power consumption.

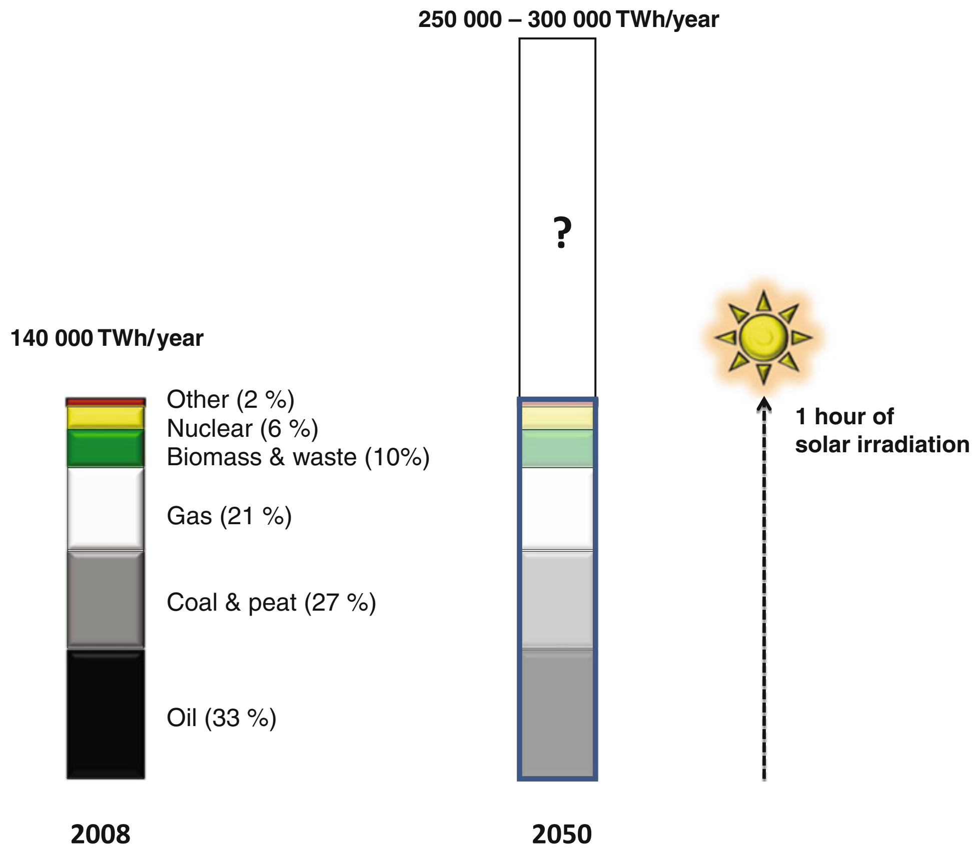


Fig. 1 The global primary energy consumption 2008 and the predicted consumption 2050 according to some selected sources. The predicted increase up to 2050 is due to an increase in population (from <7000 millions to close to 10 000 millions), a global economic growth rate similar to that during the last 40 years (mainly in non-OECD countries), but also estimates of increases in energy efficiency (International Energy Agency 2010; US Energy Information Administration 2011). For comparison the global solar irradiation during 1 h is shown

SOLAR ENERGY POTENTIAL

Solar energy is one of few alternatives that have the potential scale to meet our future demands. The solar irradiation on our planet in just 1 h equals our annual energy consumption (Fig. 1). If we could utilize as little as 0.02% of the incoming solar energy, we could satisfy all our current energy needs. This means also that only a small fraction of the land area of the earth would be required for its production. Solar energy is our most evenly distributed energy source, which has geopolitical advantages. Even in mid-Sweden, on the same latitude as Anchorage in Alaska, the annual solar irradiation (ca. 1000 kWh/m^2) is only a factor of two lower than in the Mediterranean area. The annual solar irradiation per square meter in Sweden is roughly five times larger than the annual energy consumption per square meter of an average family house in the same area (Swedish Energy Agency 2009). Thus, a device with 15–20% energy conversion efficiency covering the roof top could provide enough energy for the house, if the energy production and consumption could be balanced over the daily and yearly cycles. This simple estimate indicates that the land areas needed to provide *all* our energy from the sun would still only be similar to the area of our current buildings and roads.

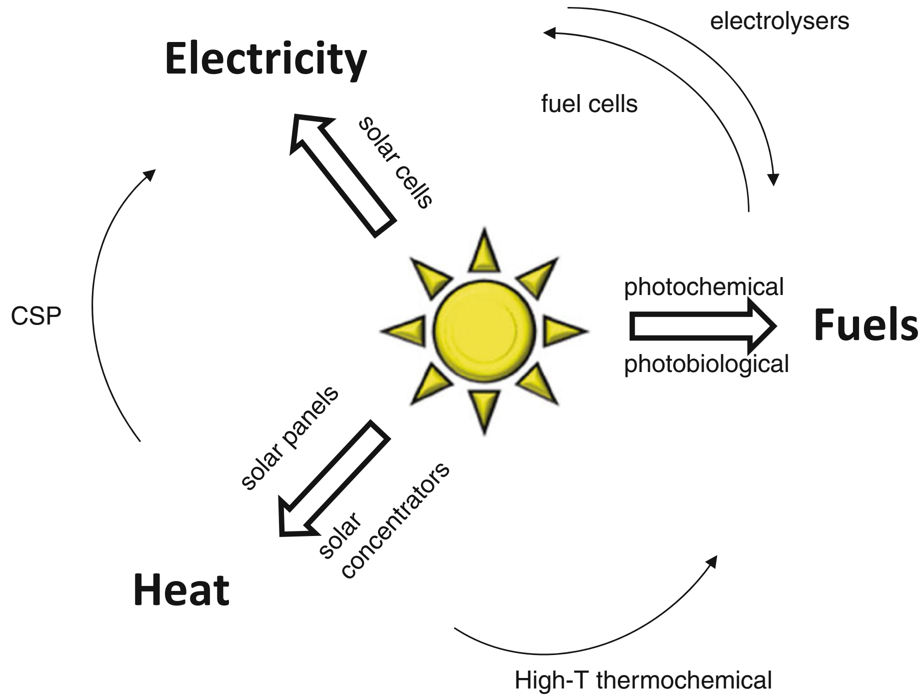
SOLAR ENERGY CONVERSION METHODS

Solar irradiation is transient and we need to capture it and convert it into a useful form that carries the energy. This carrier can be heat, electricity, or a fuel (Fig. 2).

Heat is the lowest form of energy, in the sense that all other energy forms can be efficiently converted to heat, but the conversion of heat to other energy forms is much less efficient. Heat is also difficult to store over long times. On the other hand, heat production makes use of the full solar spectrum (see below) and can be quite a simple and robust technology. Moreover, a large part of our energy is used for heating and cooling. This makes solar heat an important alternative for future solar technologies.

Solar heat can be produced in small units, such as solar panels on a roof top where flowing water or another medium is used as heat transporter. It can also be produced in larger, ground-based units with focusing mirrors reaching 400–550°C (Roeb et al. 2011). Even larger systems exist as pilot plants in, e.g., Spain, in which a field of hundreds of large mirrors track the sun and focus the irradiation on a central receiving tower at the focal point. In this way temperatures above 1500°C are reached. At this high temperature molten salts can be used to store the heat over night, which balances out variation in energy

Fig. 2 Solar energy can be converted to several useful forms: heat, electricity, and fuels. These energy carriers can also be further converted. Heat can produce electricity by CSP, or fuels by high-temperature (above 1500°C) thermochemical cycles. Solar electricity can be used to produce a fuel in an electrolyzer, and fuels can generate electricity in fuel cells. However, in each conversion step there are energy losses



production due to clouds and between day and night. The heat can be converted to electrical energy via for example a steam turbine or a Stirling engine. These technologies are known as concentrated solar power (CSP). The heat can also be used for thermochemical reactions to produce a solar fuel (Roeb et al. 2011; Styring 2012; Tamaura 2012). Because of the need to reach high temperatures such concentrating systems are mainly of interest in sunny areas in the desert region.

Electricity is an energy carrier with high energy value. As an example, electrical motors can be run at near 100% efficiency for conversion to mechanical energy, which is much better than the efficiency of internal combustion engines (ca. 30%). This gives a large potential for energy savings. However, electricity is difficult to store efficiently in large scale and over long times. Solar electricity can be produced by solar cells (photovoltaics), and the market is growing rapidly. According to the European Photovoltaic Industry Association (2012), 27.7 GW peak capacity was installed and connected to the grid in 2011, which equals the peak capacity of about 28 nuclear power plants. The actual electricity production from these cells is much lower, because of the large variation in solar irradiation during daily and yearly cycles. The variation in power production, and difficulty to store large amounts of electrical energy, is a challenge for incorporating photovoltaics in large scale into the energy system. Most of the installations are silicon cells that are rather expensive to manufacture but give up to ca. 18% energy conversion efficiency. Some thin film cells using less material have also reached the market (Edoff 2012). Several new concepts using cheaper materials and methods are presently not yet commercial, but have shown promising efficiencies, such as organic solar cells of cheap polymer blends (Inganäs et al. 2012; Ito et al. 2012; Lee et al. 2012) or dye-sensitized cells with cheaply prepared nanostructures of titanium dioxide (Hagfeldt 2012; Katoh 2012; Ozawa et al. 2012). Concepts on the research stage include nanoengineering to increase efficiency and reduce material consumption (Fukui et al. 2012; Nakano 2012).

Photovoltaics can be used as small, integrated installations on roof tops or even in electronic devices, but also in larger production units on a dedicated field. Solar electricity can also be produced from heat by CSP in larger or smaller units, as described above. Both technologies could be important for providing electrical power also to small societies in developing countries that have no electrical grid.

Fuels are attractive energy carriers as they have a very high energy density, about two orders of magnitude higher than the best batteries (Cook et al. 2010), and most fuels are easy to store and transport. The majority of our current energy comes from fuels in solid, liquid, or gaseous form. Renewable fuels produced by solar energy—so-called solar fuels—could therefore be quite compatible with existing infrastructure (Styring 2012). The most likely candidates for large-scale solar fuels production will be produced by splitting water into its components oxygen and hydrogen gas that can be used as a fuel. It is also possible to convert the hydrogen into energy-rich compounds like alcohols or hydrocarbons by carbon dioxide fixation, either in a secondary step or in direct process. The solar fuels produced can be burnt like traditional fuels, but solar fuels will not

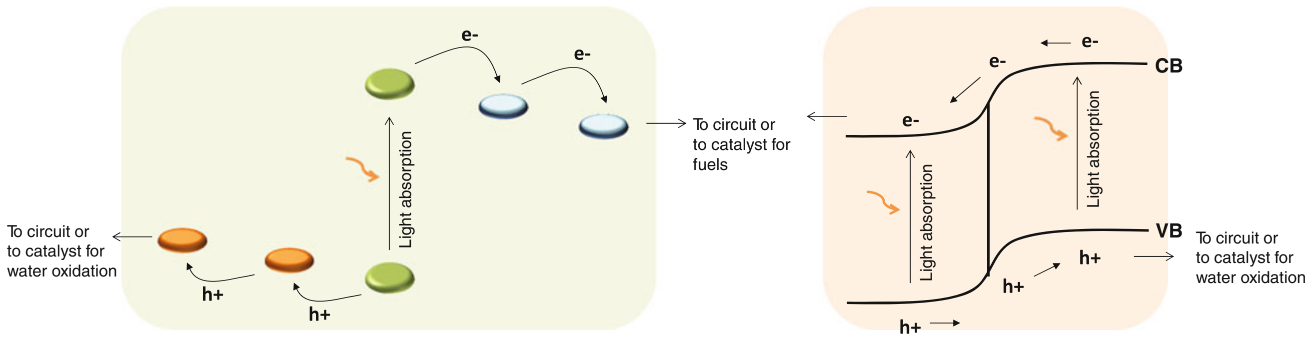


Fig. 3 Schematic diagram of the first step of solar energy conversion to electricity in solar cells or to fuels by photochemical or photobiological processes. The *left diagram* illustrates how absorption of a photon with sufficient energy leads to excitation of a molecule (*green*) to higher energy state, from which electron transfer occurs to neighboring molecules. The electrons (e−) and holes (h+) then migrate in opposite directions to the external circuit (solar cells) or to separate catalysts (solar fuels). The diagram to the *right* shows the analogous processes in a conventional bulk semiconductor cell. Photon absorption moves an electron from the valence band (VB) to the conduction band (CB) leaving a hole behind. The electric field in the junction (*thick vertical line*) between two electrode materials with different energy levels then separates the charges. Electron–hole recombination reaction reactions (not shown) in the materials (*right*) or between molecules (*left*) lead to decreases in efficiency. For many nanostructured materials, as many of those found in the references, the description lies in between the molecular and the bulk materials and the details are still being uncovered

increase the carbon dioxide level of the atmosphere. Because they were produced from solar energy, water, and carbon dioxide, they will be produced and used in a cycle that is carbon neutral.

Solar fuels from biomass are used in large scale, but the energy efficiency is limited to at best 2–3% with current plants (typically much less). There is also concern about competition for agricultural land and water resources. Instead, direct production of fuels via photochemical processes—often called artificial photosynthesis (Hammarström and Hammes-Schiffer 2009)—or in bioreactors with engineered microalgae or cyanobacteria that produce fuels directly, without bypassing biomass (Lindblad et al. 2012; Masukawa et al. 2012), have high potential for future energy production (Styring 2012). As mentioned above, thermochemical splitting of water and carbon dioxide reduction using solar concentrator towers is also a promising route. Some pilot scale thermochemical plants exist, as well as bioreactors for solar fuel production. Most of these methods are, however, on the research stage at present.

SOME PRINCIPLES AND CHALLENGES

Most of the solar energy is in the visible and infrared regions. Production of solar heat with a black absorbing material converts all photon energy to heat and can therefore utilize the entire solar spectrum (thermal energy conversion). The basic principle is different for electricity production in solar cells as well as for fuel production in photochemical systems and photosynthetic organisms (Fig. 3). Here, the efficiency depends on the energy of the incoming photons (photonic energy conversion). The photon must have sufficient energy to match the electronic energies in the molecule or material, otherwise it will not be absorbed. Thus, all photons of longer wavelength than this threshold will be wasted. However, all photons with higher energy will lose their excess energy as heat. There is therefore a balance in the optimal threshold level for a device. By having two or more different absorbers with different thresholds working in tandem the overall energy conversion efficiency can be increased.

The absorption of light leads to the separation of an electron and a “hole” in the molecule or material (Fig. 3). The electrons and holes must be further separated and collected in an external circuit as current in a solar cell. For fuel production the electrons and holes are instead collected at separate catalytic sites. The electrons are used to produce a fuel from, e.g., protons and carbon dioxide, while the holes oxidize water to molecular oxygen. Thus, water gives up electrons to the system to regenerate it and allow for further charge separation and continued fuel production.

Some of the challenges for solar energy conversion are: (1) to optimize molecules, materials or organisms, as well as device designs, to harvest the solar spectrum efficiently; (2) for photonic solar conversion: to understand and control the processes leading to charge separation and charge collection, as well as the different recombination processes and side reactions in synthetic or biological systems that lead to losses in efficiency; (3) to obtain stable materials for sustained solar energy production; and (4) to avoid rare or toxic elements that would hinder scalability of the technique, to reduce materials cost, and to find cheap and robust engineering solutions.

To develop solar energy technologies to become a major global energy resource, we need bold and enduring efforts in research, development, and commercialization, including strategic legislative measures and infrastructure investments.

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