PHOTOCONVERSION

TECHNOLOGY DESCRIPTION

Photoconversion is a generic term describing the capture of light energy by a biological, chemical or electrochemical system for subsequent use as a fuel, a chemical or electricity. It is sometimes referred to as artificial photosynthesis. When sunlight is absorbed by a photoconverter, a transient “excited” or energy-rich storage state is produced. It is this captured energy that is subsequently harnessed and utilised.

Photoconversion can be split into three components. Of these, photobiology and photochemistry are relevant to the production of a fuel such as hydrogen, while photoelectrochemistry is relevant to the production of electricity.

Photobiology

Photobiology is the study of how light interacts with biological systems. In photosynthesis, the most fundamental reaction in the evolution of life, the captured solar energy is used to drive a series of chemical reactions, resulting in the production of sugar. This procedure is carried out by plants, algae, cyanobacteria and photosynthetic bacteria.

Photochemistry

Photochemistry is a non-biological, contrived system in which solar energy is absorbed by dyes, pigments or semiconductors and then used to drive a photochemical reaction. It is possible to store the energy by producing fuels and chemicals. The energy may also be released as heat. Most photochemical reactions involve a number of stages and require light only to drive the first reaction, with subsequent steps occurring spontaneously in the dark.

Photoelectrochemistry

Photoelectrochemistry is a non-biological, contrived system in which light energy acts upon electrodes. There are two main forms of photoelectrochemical cell (PEC):

- Photoelectrochemical storage (PES) cells generate electrical energy from sunlight and store it for later use. They are, effectively, batteries that can be recharged by sunlight. Efficiency is dictated by the type of light and dark electrode selected. An unusual, and weak, feature of this system is that the same chemical species is used both to collect the solar energy and for energy storage. Solar efficiencies are low and their energy production potential is considered to be limited.

- Electrochemical photovoltaic (ECPV) cells are functional equivalents of conventional solid state semiconductor photovoltaic cells: they produce DC electric current on illumination. It is thought that ECPV cells might offer the potential for production cost advantages because the light reactive centre is on the electrode surface instead of being embedded within a semiconductor. This suggests that, with direct illumination, a rough electrode surface[1] (with a high surface area), and hence a crude and inexpensive design, could be used for ECPV. By contrast, the effectiveness of a solid state PV system depends on a uniform and accurate junction and requires a light-absorbing surface layer.

MARKET

Commercial markets are limited at present, and significantly more effort is required before the technologies become commercialised. Initial applications may be in consumer products with a very lower power requirement.

BENEFITS

There is a wide range of photoconversion technologies. These generally attract interest because:

- they use freely available sunlight to drive the reactions
- many systems operate in water, which is widely available
- the processes tend to have low ecological impact (are non-polluting)
- the processes do not add to carbon dioxide (CO_2) emissions, ie they don't contribute to global climate change
- in some cases they are, or they mimic, natural systems.

Like other renewable energy technologies, photoconversion technologies could contribute to the diversity and security of energy supply. They could also help the UK to meet its targets relating to sustainability and greenhouse gas emissions.

TECHNOLOGY STATUS

This section briefly reviews some of the key variants of photoconversion within the three categories.

Photobiology

Useful products from algal photosynthesis

Micro-algal photobioreactors have been suggested for use in long-term manned space missions to regenerate oxygen, absorb CO_2 and treat wastes. Anticipated improvements in the technology are likely to focus on enclosed controlled photobioreactors, an area of potential relevance to hydrogen production.

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[1] A rough surface enables improved light transfer. This type of system design reduces charge carrier loss, thereby improving charge separation efficiency.

The high cost of mass producing algal cultures is the key blockage preventing the move to competitive industrial plants.

Hydrogen production by photosynthetic micro-organisms

A number of scientists in the field have concluded that photoconversion systems for producing hydrogen from water are a promising option for an ecologically clean future. The design of photobioreactors for such systems is, once again, highlighted as a significant development feature.

Outdoor hydrogen production has been demonstrated for several months using a mutant *Anabaena variabilis* that can no longer take up hydrogen.

There is ongoing research in the USA into:

- hybrid biomass gasification that produces hydrogen for a phosphoric acid fuel cell

- the development of efficient green algal strains that will produce hydrogen from water under ambient conditions.

A recent advance, at the laboratory scale, has been the substantial inactivation of oxygen evolution and the subsequent production of large amounts of hydrogen. This is significant because the enzyme that releases hydrogen is sensitive to oxygen.

It has been suggested that the first biohydrogen production technology to come on-line is likely to be a hybrid system that combines biomass gasification with biological gas conditioning. Following this will be two-stage algal systems.

In the longer term, photobiological water splitting (biophotolysis) using micro-algae is thought to hold potential.

Photochemistry

Artificial photosynthesis

The term artificial photosynthesis describes man-made structures that allow solar photochemistry to produce fuels and useful chemicals from simple substrates such as water, CO_2 and nitrogen. Four basic components are required:

- antennae for harvesting the light
- a reaction centre for separating charge
- catalysts
- a membrane to separate the end products.

While there is some ongoing research work, it is thought unlikely that these systems will prove to be commercially viable for large-scale solar energy conversion because of their limited stability.

Photochemical heat storage systems

Photochemical heat storage systems are considered too expensive and inefficient to be worth further development. Furthermore, it is thought that, even if efficiencies were nearer to 15% (the ambitious likely maximum for a single photosystem) rather than the ~1% achieved to date, the economics would still be extremely unfavourable. There are also two significant scientific challenges:

- the extreme "cleanness" required of both the photochemical and the thermochemical steps
- the fact that sunlight absorption by these systems is poor.

Photoelectrochemistry

ECPV – dye-sensitised nanocrystalline cells

The area of dye-sensitised nanocrystalline cells is where most recent advances have been made. Gratzel and his co-workers at Lausanne developed dye-sensitised nanocrystalline solar cells that, on small areas, have now achieved efficiencies of up to 10%. These systems comprise a solid photoelectrolytic cell coated with a dye, which harvests the solar radiation.

Such dye-sensitised photoelectrochemical cells may well offer the best prospects for the future of all the photoconversion options currently available, although they still have a number of development hurdles to overcome. Their main advantages are:

- they are cheaper and easier to produce than their solid state equivalents
- they are stable
- they offer practical application.

Photovoltaic cells of this type are cheaper, largely because they can operate without high-cost, crystalline semiconductor materials but can still achieve solar to electrical energy conversion efficiencies of up to 10%. Their laboratory-scale performance is similar to that of amorphous silicon, but manufacturing costs are likely to be lower.

Until fairly recently, the advantages of dye-sensitised photovoltaic cells have been obscured by the danger of electrolyte leakage. Efforts to solidify the solution have proved difficult although, in May 2000, Toshiba announced that they had isolated and identified chemicals that enabled solidification of the electrolyte within the current manufacturing process. Furthermore cell production is possible using a plastic substrate and a transparent electrode. This is significant because the cells would be both lighter and suitable for window mounting, a market application considered to have significant potential and one that is not available to silicon cells.

Identifying a potential new market area is a significant boost to facilitating the market entry of a new product. It means that the product will not simply be "an alternative to a more tried and tested technology".

The technology has been licensed to industrial corporations in Europe and Australia (as well as in Japan) for applications that include the supply of electric power to stand-alone consumer devices such as electronic displays and mobile communications.

Organic photovoltaic devices

Organic photovoltaic devices constitue the second key research area for photoconversion. According to some researchers, organic photovoltaic devices are a possible contender for incorporation in semiconductor photovoltaic devices. The key potential advantage is the fact that they can be processed over large areas at relatively low temperatures, thereby reducing manufacturing costs. It is the need for high-temperature processing in a high vacuum environment that currently keeps costs relatively high for the inorganic semiconductor PV system.

The challenges in developing organic semiconductors of this type are, nevertheless, considerable. Development requires new materials, new methods of manufacture, new device architectures and new substrate and encapsulation materials. However, molecular semiconductors are widely used for xerographic copying and laser printing, so techniques and experience do exist. Most relevant is the development of molecular semiconductor light emitting diodes (LEDs), which are very efficient and are currently being commercialised. The most likely applications could be high-turn-over, low tech applications such as toys.

Problems that need to be overcome include poor operational stability, sensitivity to oxygen and (by no means least) the need to enhance the efficiency of organic solar devices. It is in this last-mentioned area that most research efforts are currently focused. Some researchers envisage the commercial application of organic photovoltaic cells over the next few years – a process that could be accelerated as the technology for thin film polymer and molecular semiconductors for display applications becomes established.

Photoelectrochemical storage (PES) cells

A recent review shows that some progress has been made in the development of PES cells, although the technology has not yet moved out of the fundamental research bracket. Many challenges remain, and the length of the list of parameters still needing to be optimised suggests that medium-term prospects for this technology are limited.

TARGETS FOR COMMERCIAL COMPETITIVENESS

The longer-term targets for photoconversion technologies are that they should become competitive with other means of electricity production and/or produce competitive fuels. Early applications involving consumer products would have targets relevant to the specific host product.

RESEARCH AND DEVELOPMENT ISSUES

Some of the development issues have been noted in the section on technology status. However, in general terms, two key areas for nearer-term development have been identified:

- improving the robustness of nanocrystalline dye-sensitised ECPV cells
- the further development of organic photovoltaic devices.

Areas that require further development to acquire commercial potential but that are much less advanced include:

- the successful development of stable photoelectrochemical cells that allow the storage and release of energy to be managed in a controlled and practical manner
- the optimisation of hydrogen production in photobiological systems.

NON-TECHNICAL ISSUES

There are likely to be a number of non-technical issues relating to the implementation of photoconversion technologies but, at this stage in the technology's development, these are not believed to have a high priority.

UK INDUSTRY STRENGTHS

The only UK manufacturer known to be involved in this area of research is Johnson Matthey. The company is looking to the third generation of solar cells, aiming for devices that are cheaper and more efficient. About 15 UK academic research groups are also known to be working on photoconversion.

RATIONALE FOR A DTI PROGRAMME

There does not appear to be a strong case for a separate DTI programme on photoconversion: the expression of industrial interest is limited, and prospects (except in the ECPV and organic PV areas) are uncertain. It is likely that some fundamental research will continue to be supported by the Research Councils.

PROPOSED ACTIONS AND TARGETS

1. Include R&D on ECPV and organic PV within the new PV programme to make more effective use of the existing science base and provide a focus for industrial involvement.
2. Maintain a watching brief on photoconversion in general, and undertake another review in three to five years' time.