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Emerging and future bioenergy technologies

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Introduction

In recent years biotechnology has featured in most “top ten” lists of emerging technologies. Energy supply based on biomass occupies a similar position in the list of emerging technologies for renewable energy, and yet the interface between biotechnology and power generation remains in most cases wide open for development.

There is no generally acknowledged definition of the term “emerging technologies”. A recent book from Wharton Business School defines emerging technologies as “*science based innovations that have the potential to create a new industry or transform an existing one*[1]”. The authors distinguish between two kinds of emerging technologies: discontinuous and evolutionary.

Discontinuous technologies derive from radical science-based innovations, while evolutionary technologies arise at the junctions of research streams that were previously separate. The latter definition applies especially to biomass-based energy technologies, where enormous synergies could be gained from joining together disconnected areas of scientific investigation.

One of the biggest challenges to the continuing use of fossil fuels is associated with global warming caused by CO_2 emissions. This report concentrates on biomass-based energy technologies, but biotechnology could also contribute to the development of CO_2-neutral power generation systems based on fossil fuels. There are essentially two distinct areas where biotechnology can contribute:

a) The area of traditional biotechnology, so-called white biotechnology, is related to the technical use of fermentation processes or enzymes in downstream processes of biomass conversion. This is firmly established and an integral part of the processes described below.

b) The area of green biotechnology is related to the genetic engineering of plants in order to tailor biomass with respect to their efficiency as energy resource. This area is only emerging and has only been explored superficially. To date almost only biomass as energy source has been investigated that was available from traditional cropping or foresting systems. The challenge is now to establish small scale prediction systems allowing to establish structure-function relationships between biomass composition and its convertibility in energy conversion systems, in order to explore a broad range of generated biodiversity also in energy cropping systems.

The IEA has set up a useful taxonomy setting out the different fields of research whose integration will help create sustainable biomass-based energy technologies (Figure 4). The field of *biomass resources* is mainly concerned with optimising existing production systems for maximum energy output. Here especially, green biotechnology will provide tools to broaden genetic variability and develop novel feedstocks for energy production systems. *Supply systems* represent the largest technical challenge in optimising bioenergy generation and use, as supply is

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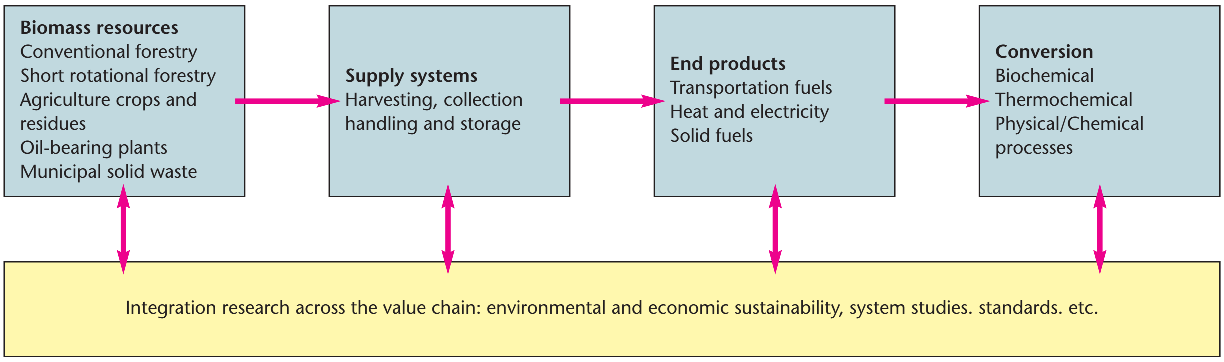
[1] Day and Shoemaker, 2000; 2

Figure 4. The IEA taxonomy shows the different fields of research whose integration will aid the development of sustainable biomass-based energy technologies.



always related to energy consumption and may well be influenced by the development of decentralised power generation systems. *Conversion* depends in part on the development of white biotechnologies to establish commercially-feasible energy production systems, whereas research into *end products* is oriented more towards engineering and the optimisation of plant and machinery for use with biomass.

Current developments

Table 6 uses the IEA taxonomy to summarise the major emerging and future technologies in bioenergy. Emerging technologies are defined as above, while future technologies are those that will take more than ten years to reach the market.

"Bioenergy" is sometimes thought of as old-fashioned and for poor people. To distinguish modern technology from traditional practices, the term "modern bioenergy" is sometimes used to cover more sophisticated combustion systems (at domestic, industrial or power-plant scale), gasification, hydrolysis, pyrolysis, extraction and digestion technologies.

Most of these technologies have been available for decades, but have not been economic. Recent advances in performance have made them much more attractive, especially in view of their ability to improve the environment and create jobs at the same time as making use of available energy resources.

There are five fundamental forms of bioenergy use:

1. "Traditional domestic" use in developing countries, burning firewood, charcoal or agricultural waste for household cooking (e.g. the "three stone fire"), light-

Table 6. Emerging and future technologies in bioenergy.

Stage	Emerging technologies	Future technologies
Biomass resources	New energy crops New oilseed crops Bio-waste management	Bioengineering of new energy plants Development of low-energy agricultural production systems Aquatic biomass (algae) IT methods in land and biological systems management
Supply systems	Use of new agro-machinery Biomass densification Other simple pretreatments (e.g. leaching) Logistics of supply chains	Biorefining Biotech-based quality monitoring throughout the whole procurement chain IT tools for supply chain modelling and optimal management
Conversion	Advanced combustion Co-combustion Gasification Pyrolysis Bioethanol from sugar and starch Bioethanol from lignocellulosic material Biodiesel from vegetable oils Advanced anaerobic digestion	Biohydrogen (hydrogen from bioconversion of biomass) Plasma-based conversions Advanced bioconversion schemes Other novel conversion pathways (e.g. electrochemical) Novel schemes for down-stream processing (e.g. of pyrolytic liquids or synthetic FT-biofuels)
End products	Bioheat Bioelectricity Transport biofuels Upgraded solid biofuels	Use of hydrogen in fuel cells Use of FT-biofuels in new motor-concepts e. g. CCS (Combined Combustion Systems) New bio-products (biotech) Complex, multi-product systems (IT) CO_2 sequestration; other new end-use "cultures" (e.g., user-friendliness, "closed cycle")
System integration	Normalisation and standards Best practices Economic/ecological modelling and optimisation	IT-based management Socio-technical and cultural design of applications Sustainability based on global as well as local effects

ing and space heating. Energy conversion efficiency is generally 5–15%.
2. "Traditional industrial" use for processing tobacco, tea, pig iron, bricks, tiles etc. The biomass feedstock is often regarded as "free", so there is generally little incentive to use it efficiently and energy conversion efficiency is commonly 15% or less.
3. "Modern industrial" use, in which industries are experimenting with technologically-advanced thermal conversion technologies. Expected conversion efficiencies are in the range 30–55%.
4. Newer "chemical conversion" technologies (fuel cells). These are capable of bypassing the entropy-dictated Carnot restriction that limits the conversion efficiencies of thermal conversion units.
5. "Biological conversion" techniques, including anaerobic digestion for biogas production and fermentation for alcohol e. g. from lignocellulosic raw material.

In general, biomass-to-energy conversion technologies have to deal with feedstocks that vary widely in their mass and energy density, size, moisture content and availability. Modern industrial installations therefore often employ hybrid technologies, in which fossil fuels are used to dry and pre-heat the biomass before it is burned, and to maintain production when biomass is unavailable.

Bioenergy conversion technologies

Among the most important bioenergy conversion technologies are:

Direct-combustion processes

Feedstocks for direct combustion are often residues such as woodchips, sawdust, bark, hogfuel, black liquor, bagasse, straw, municipal solid waste (MSW) and wastes from the food industry. Direct-combustion furnaces are used to produce either direct heat or steam.

Co-firing

A modern practice is the co-firing of a fossil-fuel, usually coal, with a bioenergy feedstock. Co-firing has a number of advantages, especially for electricity production. It may be relatively cheap to modify existing fossil-fuel equipment for co-firing, so this can be a cost-effective way to cut fuel bills or meet new emission targets.

Thermochemical processes

Thermochemical processes do not necessarily produce useful energy directly. Instead, they use controlled conditions of temperature and oxygen level to convert the original bioenergy feedstock into more convenient energy carriers such as producer gas, oil or methanol. Compared to the original biomass, these energy carriers either have higher energy densities – and lower transport costs – or more predictable and convenient combustion characteristics, allowing them to be used in internal combustion engines and gas turbines.

Carbonisation

Combustion is an age-old process optimised for making charcoal. In traditional charcoal-making, wood is placed in mounds or pits, covered with earth to keep out oxygen, and set alight. Modern charcoal processes are more efficient; large-scale industrial production of charcoal in Brazil, for instance, achieves efficiencies of over 30% by weight.

Pyrolysis

Pyrolysis is a step on from carbonisation in which biomass is processed at high temperatures and the absence of oxygen, sometimes at elevated pressure. The shortage of oxygen prevents complete combustion, and instead the biomass is broken down to a mixture of simple molecules (methane, carbon monoxide and hydrogen) known as producer gas. Charcoal, coke and other heavy materials are often produced as residue.

Gasification

With careful control of temperature and oxygen level it is possible to convert virtually all the raw material into gas. Gasification, which is a further development of pyrolysis, takes place in two stages. First, the biomass is partially burned to form producer gas and charcoal. In the second stage, the carbon dioxide and water produced in the first stage are chemically reduced by the charcoal, forming carbon monoxide and hydrogen. The composition of the resulting gas is 18–20% hydrogen, 18–20% carbon monoxide, 2–3% methane, 8–10% carbon dioxide and the rest nitrogen. Gasification requires temperatures of around 800°C or more to minimize the residues of tars and high hydrocarbons in the product gas.

Catalytic liquefaction

Catalytic liquefaction has the potential to produce higher-quality products of greater energy density than are possible with other thermochemical processes. These products should also require less processing to get them into marketable form. Catalytic liquefaction is a low-temperature, high-pressure thermochemical conversion process carried out in the liquid phase. It requires either a catalyst or a high partial pressure of hydrogen. Technical problems have so far limited the applications of this technology but the quality of the products justifies the expenses. Further R&D activities for optimal concepts of these conversion strategies must be applied

Biochemical processes

The use of yeast to produce ethanol is an ancient art. However, in more recent times micro-organisms have become regarded as biochemical "factories" for treating and converting most forms of human-generated organic waste. Microbial engineering has encouraged the use of fermentation technologies (aerobic and anaerobic) for the production of energy (biogas) and fertilisers, and for removing unwanted products from water and waste streams.

Anaerobic fermentation

Anaerobic reactors are generally used to make methane-rich biogas from manure (human and animal) and crop residues. Anaerobic digesters of various types are widely distributed throughout China and India. They are ideal for rural areas because they improve sanitation as well as producing fuel and fertiliser. Large digesters are becoming useful in environmental protection applications such as removing nitrates from water supplies.

Methane production in landfills

Anaerobic digestion in landfills is brought about by the microbial decomposition of the organic matter in refuse. Landfill gas is on average 60% methane and 40% carbon dioxide.

Ethanol fermentation

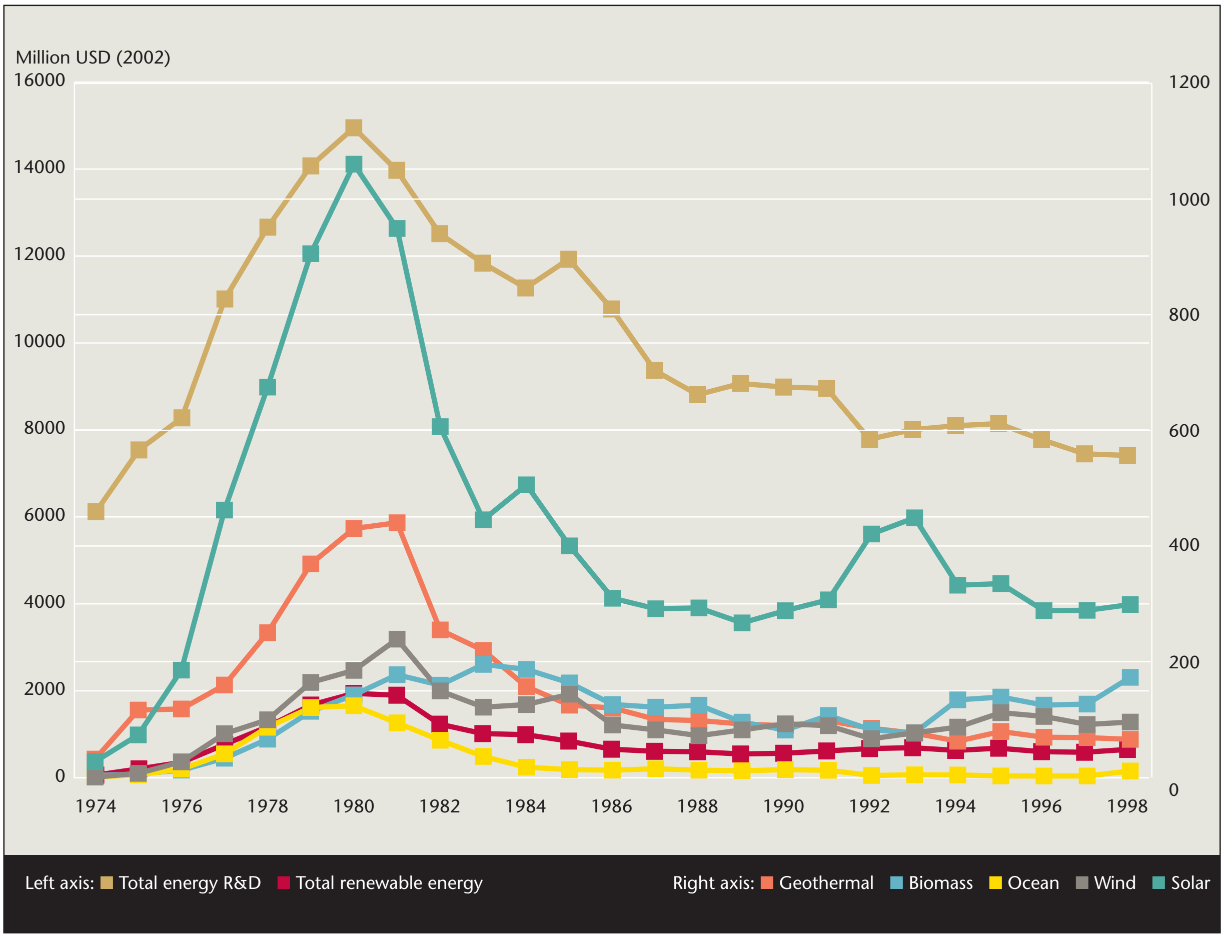
Improvements in fermentation technology have made bioethanol economically competitive, as well as environmentally beneficial, as a petroleum substitute and fuel enhancer. Bioethanol programmes exist in Brazil, Zimbabwe, and the USA.

The commonest bioethanol feedstock in developing countries is sugar cane, due to its high productivity when supplied with sufficient water. Where water availability is limited, sweet sorghum or cassava may be preferred. Other feedstocks include saccharide-rich sugar beet and carbohydrate-rich potatoes, wheat and maize. Recent advances in the use of cellulosic feedstock may allow bioethanol to be made competitively from woody agricultural residues and trees.

Biodiesel

Vegetable oils have been used as fuel in diesel engines for over a century. Whilst it is feasible to run diesel engines on raw vegetable oils, in general these oils must first be

Figure 5. Development in governmental R&D expenditures from 1974 to 1998. Figures are in millions of USD with a 2002 price level. Data downloaded via: http://www.iea.org/stats/files/rd.htm



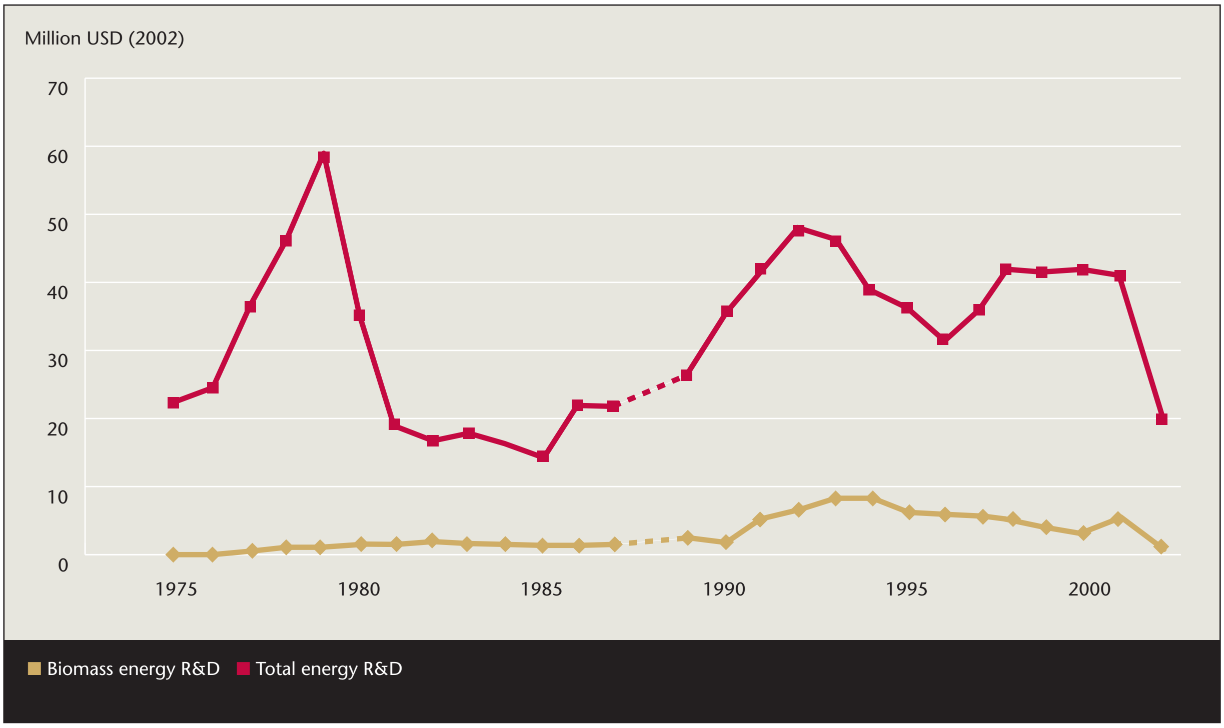


Figure 6 . Development in Danish governmental R&D expenditures from 1975 to 2002. Figures are in millions of USD with a 2002 price level. Data downloaded via: http://www.iea.org/stats/files/rd.htm. No figures available for 1988.

chemically transformed so that they more closely resemble petroleum-based diesel.

The raw oil can be obtained from a variety of annual and perennial plant species. Perennials include oil palms, coconut palms, physica nut and Chinese tallow tree. Annuals include sunflower, groundnut, soybean and rapeseed. Many of these plants can produce high yields of oil, with positive energy and carbon balances.

As a rule, most of the emerging biomass technologies are those now receiving R&D funding from government and other sources. Future technologies, on the other hand, depend strongly on interactions between current emerging technologies and generic developments in biotechnology and IT. These interactions can only be reliably achieved by systematically steering biotech and IT research towards bioenergy subjects – a critical task on the research agenda for the next decade. We should also mention the critical role that social and cultural aspects are expected to play in the future of this complex field.

R&D indicators in biomass for energy

Since emerging technologies, on the Wharton definition, are closely related to science-based innovations, it is logical to examine some traditional indicators of research and development activity in biomass energy technologies.

It is well known that global government R&D spending on energy has decreased steadily since its peak at around the time of the second oil embargo in 1979. According to the IEA, total expenditure on government energy R&D in IEA member countries fell by more than half during the 1980s and 1990s, but with relatively large variations between individual countries and between technologies. Biomass-related energy R&D has managed to increase its share of government spending, in both relative and absolute terms, in the last decade or so (Figure 5). The opposite is the case for Denmark where the biomass related governmental R&D has decreased after a peak in early 1990's (Figure 6).

Breakthroughs in energy-related biotechnology do not have to stem from targeted energy research, of course. They can equally well be a consequence of generic research programmes.