The Application of Biotechnology to Industrial Sustainability - A Primer

SUSTAINABLE DEVELOPMENT

OECD

THE APPLICATION OF BIOTECHNOLOGY TO INDUSTRIAL SUSTAINABILITY – A PRIMER

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

FOREWORD

This short paper is based on the OECD publication, "The Application of Biotechnology to Industrial Sustainability". The Task Force on Biotechnology for Sustainable Industrial Development of the OECD's Working Party on Biotechnology contributed to this primer which was prepared by the Chairman of the Task Force, Dr. John Jaworski, Industry Canada, Canada. Special thanks are due to Dr. Mike Griffiths (OECD Consultant) as well as to those who contributed to the case studies set out in the publication on which the primer is based.

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EXECUTIVE SUMMARY

Biotechnology provides tools for adapting and modifying the biological organisms, products, processes and systems found in nature to develop processes that are eco-efficient and products that are not only more profitable but also more environment-friendly. It is also providing an increasing range of tools for industry to continue improving cost and environmental performance beyond what could normally be achieved using conventional chemical technologies.

Biotechnology is proving its worth as a technology that can contribute to sustainable industrial development. The OECD has collected and analysed case studies[1] of the application of biotechnology in such diverse sectors as chemicals, plastics, food processing, textiles, pulp and paper, mining, metal refining and energy. The case studies show that biotechnology can not only reduce costs but also reduce the environmental footprint for a given level of production. In some cases, capital and operating costs decreased by 10-50%. In others, energy and water use decreased 10-80% while the use of petrochemical solvents was reduced by 90% or eliminated completely. In a number of cases, biotechnology enabled development of new products whose properties, cost and environmental performance could not be achieved using conventional chemical processes or petroleum as a feedstock.

World-wide, there is growing appreciation that the management and utilisation of natural resources need to be improved. The amounts of waste and pollution generated by human activity must be reduced on a large scale. There is realisation that making industry more sustainable can provide the means of reducing environmental impacts or even improving the environment while yielding goods and services that can provide jobs, reduce poverty and improve the quality of life for a growing world population.

Developing a sustainable bio-based economy that uses eco-efficient bio-processes and renewable bio-resources is one of the key strategic challenges for the 21st century. Improved understanding of biodiversity, ecology, biology and biotechnology is making it possible both sustainably to increase biomass productivity in forestry and agriculture as well as to utilise that biomass and waste organic materials in a highly efficient and sustainable manner. Without such advances in science and technology, the move to a more bio-based economy would result in rapid depletion of renewable resources and environmental degradation.

A more bio-based economy offers hope both for developed and developing countries. For developed countries, it presents the opportunity to use their technological capabilities for national security of energy and chemical supply. For developing countries, it provides the potential at least partially to leapfrog the age of fossil fuels and petrochemicals to the age of more environment-friendly biofuels and biochemicals that can be produced locally, improving the economy and quality of life. Visionary thinking is required among industry, government as well as the research and environmental communities to shape an approach to a more bio-based economy that will yield optimal economic, environmental and societal benefits for developed and developing countries.

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1 OECD 2001. The Application of Biotechnology to Industrial Sustainability (www.oecd.org/sti/biotechnology).

Introduction

Human activities – industrialisation, urbanisation, agriculture, fishing and aquaculture, forestry and silviculture as well as petroleum and mineral extraction – have profound impacts on the world's environment as well as on the quality of life. As a result, there is a growing appreciation that nationally, regionally and globally the management and utilisation of natural resources need to be improved and that the amounts of waste and pollution generated by human activity need to be reduced on a large scale. This will require a reduction and, if possible, elimination of unsustainable patterns of production and consumption. As a result, emphasis is growing on industrial sustainability because this is increasingly recognised as a key means of bringing about such reduction of environmental impacts and improving quality of life.

What is Industrial Sustainability?

The World Commission on Environment and Development (Brundtland 1987) has provided insight on sustainable patterns of production and consumption through its description of sustainable development:

> *"Sustainable Development: Strategies and actions that have the objective of meeting the needs and aspirations of the present without compromising the ability to meet those of the future".*

This definition of sustainable development can be adapted to provide a conceptual definition of industrial sustainability:

> "*Industry is sustainable when it produces goods and services in such a manner as to meet the needs and aspirations of the present without compromising the ability of future generations to meet their own needs".*

A closer look shows that industry is sustainable when it is:

- **economically viable (uses natural, financial and human capital to create value, wealth and profits).**
- **environmentally compatible** (uses cleaner, more eco-efficient products and processes to prevent pollution, depletion of natural resources as well as loss of biodiversity and wildlife habitat).
- **socially responsible** (behaves in an ethical manner and manages the various impacts of its production through initiatives such as Responsible Care).

This "triple bottom line" for industry is captured in a quote from the Shell Report 2000:

> *"Excellent environmental performance is meaningless if no wealth is created. Wealth in a destroyed environment is equally senseless. No matter how wealthy, a society fundamentally lacking in social equity cannot be sustained."*

Moving Toward More Sustainable Industries

Developing sustainable industries implies constantly assessing and improving industrial performance. The aim is to uncouple economic growth from environmental degradation so that industry will be more profitable and, simultaneously, environmental quality will also improve.

Economic growth provides jobs and income, goods and services and opportunities to improve the standard of living for an increasing world population. Environmental protection recognises the intrinsic value of nature and living things. It also recognises the potential of organisms living in ecosystems to provide insights and the means for developing sustainable industrial products, processes and production systems. Sustainable industrial development can be achieved if the three requirements (economic, environmental and social) outlined above are applied to guide the pathway and shape the process by which industry and the economy grow.

At a very basic level, sustainable industrial development means doing more with less – increasing eco-efficiency, that is, decreasing the level of pollution and at the same time the amount of energy, material and other inputs required to produce a given product or service. A major way of accomplishing this is through cleaner production. Cleaner production involves a paradigm shift where innovation is used to develop:

- **processes** and production systems which:
  - save costs and are more profitable because they are less wasteful of materials and energy (resulting in less emissions of greenhouse gases, persistent organic chemicals and other pollutants).
  - enable greater and more efficient utilisation of renewable resources (energy, chemicals and materials), lessening our dependence on non-renewable resources such as petroleum and reducing associated greenhouse gas emissions.
- **products** which are:
  - better performing, more durable and don't persist after their useful life.
  - less toxic, more easily recyclable and more biodegradable than their conventional counterparts.
  - derived as much as possible from renewable resources and contribute minimally to net greenhouse gas emissions.

Technology, Cleaner Production and Sustainability

Technological innovation is a key means of achieving cleaner production and sustainable industrial growth. However, "cleaner" should not be confused with "sustainable". Sustainable means clean enough to meet the needs of the present without compromising the ability of future generations to meet their own needs. Making the distinction between "cleaner" and "sustainable" requires the tools to assess and compare the performance of different technologies used for industrial production.

Companies that have to take decisions on implementing and improving production processes can develop these processes on the basis of best available technologies. Some sources of information already exist on best available technology, for example, the European Integrated Pollution Prevention and Control Bureau[2] or the UNEP International Cleaner Production Information Clearinghouse[3].

Scientifically validated criteria and methods for evaluating the long-term sustainability of industrial production are still being developed (see for example the Web site of the Canadian National Round Table on the Environment and the Economy: www.nrtee-trnee.ca). Nevertheless, it is possible to estimate what is sustainable ("clean enough") from an environmental perspective based on the present situation and some simple assumptions. This helps answer the question:

> "*If one is to approach environmental sustainability while achieving sustained economic growth, what should be the environmental performance targets for technology at the R&D phase today compared to the performance of technology which is currently the industry standard?"*

To answer this question, it is necessary to determine what environmental performance will be required of technology in order to keep the environmental "footprint" (impact) of industrial production at a constant level. Experience has shown that environmental footprint of industry is directly proportional to the level of economic activity (that is, if production doubles, then the environmental footprint doubles), other things being equal. So, as production increases so too must the environmental performance, or "eco-efficiency", of technology used if concomitant increases in the environmental footprint of industrial activities is to be avoided.

What this means is that new technologies, which bring improvements in production, must also bring improvements in "eco-efficiency". As is explained more fully in Box 1, the lag between the R&D phase of new technologies and the point at which these become industry standards, means that work at the R&D stage today needs to target quite significant improvements in environmental performance.

If the present environmental impact of existing industrial production is not sustainable, then the environmental performance targets for new technology to help address this will have to be raised even higher. The following sections show that advances in technology, especially biotechnology, can help deliver improvements in environmental performance beyond the factor of 3-4 identified in the example in Box 1.

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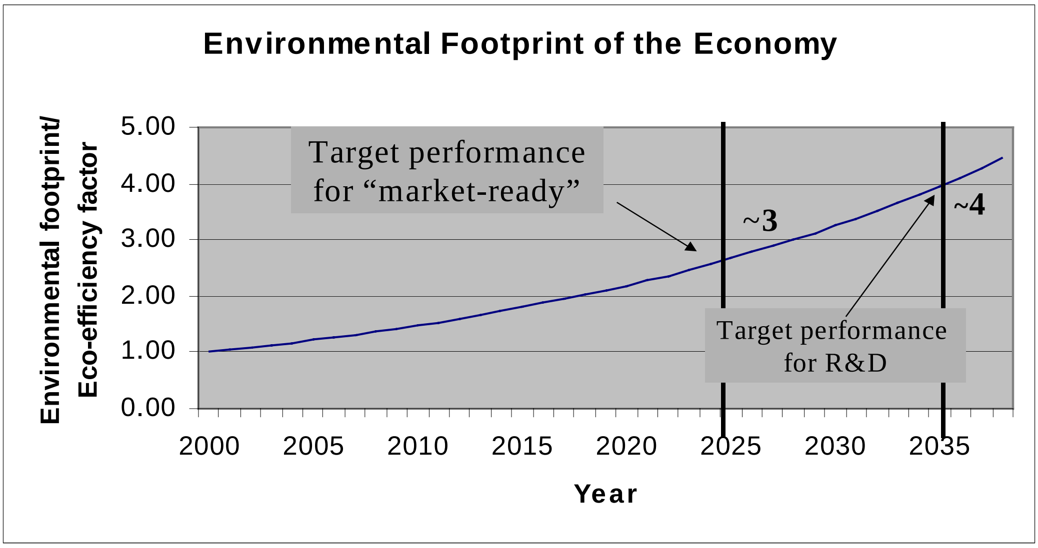
2 European Integrated Pollution Prevention and Control Bureau (EIPPCB), Web site: http://eippcb.jrc.es

3. UNEP (1999), International Cleaner Production Information Clearinghouse, CD Version 1, United Nations Environment Programme, Division of Technology, Industry and Economics, Paris. Also available on the Web site: www.emcentre.com/unepweb/.

Box 1: Eco-efficiency of the economy to keep the environmental footprint constant



The graph sets out a picture of a growing economy over time. The curve represents two functions. First it represents the rising environmental footprint or impact from 4% economic growth without any changes in the environmental performance of the technology used. And second, the same curve delineates the factor of eco-efficiency gain required to deliver the same growth with no impact on the environmental footprint.

So the graph in Box 1 shows that in order to bring the environmental impact back to its original level:

- technologies that are ready to be introduced into the market today (it takes an average of 25 years for these to become average industry practice) should have an environmental performance at least three times better than the current industry average (that is, emissions only 33% of present).

- technologies at the R&D stage today (it will take an average of 35 years for these to become average industry practice) should have an environmental performance at least four times better than the current industry average (that is, emissions only 25% of present).

The assumptions built into Box 1 include:

- environmental impacts are directly proportional to level of economic activity.

- economic growth (the rate of increase in production), for purposes of this analysis, is set at 4% per year.

- improving the environmental performance ("eco-efficiency") of production technology decreases the environmental footprint for a given level of economic activity.

- in order to be adopted, a technology must provide a significant net positive value in terms of its economic and/or environmental performance.
- if newly developed technology is now beginning to be introduced into industry, it will take an average of 25 years for it to become the average performance of the industry as a whole.
- technologies at the R&D stage today will take an average of 10 years to develop to the "market-ready" stage, that is, where it is attractive for industry to begin adopting them.

Learning from Nature: Biomimicry and Biotechnology

It is difficult to achieve a four-fold improvement in environmental performance through incremental improvements in conventional production technologies. Improvements of this magnitude usually call for a paradigm shift.

For a growing number of companies, the inspiration for such a paradigm shift is coming from the products and processes found in natural ecosystems and the organisms that live in them. **Biomimicry** is the name coined for this approach in which industrial production systems imitate nature. **Industrial biotechnology** is that set of technologies that come from adapting and modifying the biological organisms, processes, products, and systems found in nature for the purpose of producing goods and services.

The organisms, processes, products and systems found in natural ecosystems have evolved over millions of years to become highly efficient. For example, all energy in natural ecosystems is renewable and is initially captured from sunlight through photosynthesis. Also, all bio-organic chemicals and materials are renewable, biodegradable and recycled. There is no such thing as "waste" – the by-products of one organism are the nutrients for another. Most, if not all, metabolic processes are catalysed by enzymes and are highly specific and efficient.

Biotechnology has evolved over the last 25-30 years into a set of powerful tools for developing and optimising the efficiency of bioprocesses and the specific characteristics of bioproducts. This increase in efficiency and specificity has great potential for moving industry along the path to sustainability. Increased efficiency allows for greater use of renewable resources without leading to their depletion, degradation of the environment and a negative impact on quality of life. Biotechnology can become an important tool for decoupling economic growth from degradation of the environment and the quality of life. Biotechnology can also enable the design of processes and products whose performance cannot be achieved using conventional chemistry or petroleum as feedstock.

Here are some examples of some of the industrial efficiency tools now coming from the application of biotechnology:

- Enzymes extracted from naturally occurring micro-organisms, plants and animals can be used biologically to catalyse chemical reactions with high efficiency and specificity. Compared to conventional chemical processes, biocatalytic processes usually consume less energy, produce less waste and use less organic solvents (that then require treatment and disposal).
- By imitating natural selection and evolution, the performance of naturally occurring enzymes can be improved. Enzymes can rapidly be 'evolved' (this technique is called "**molecular evolution**") through mutation or genetic engineering and selected using high-throughput screening to catalyse specific chemical reactions and to optimise their performance under certain conditions such as elevated temperature.

- The metabolic pathways of micro-organisms can also be modified by genetic engineering. The aim is to turn each cell into a highly efficient "mini reactor" that produces in one step and at high yield what would take an organic chemist a number of steps with much lower yield (this technique is called "**metabolic engineering**").

- A further improvement on metabolic engineering involves engineering the enzymes in the optimal configuration onto the cell membrane and when the cell is ruptured the cell membrane becomes a **bio-catalytic surface** that provides the high efficiency of metabolic engineering without the energy penalty of keeping the organism alive.

- Plant biomass can be processed and converted by fermentation and other processes into chemicals, fuels and materials that are renewable and result in no net emissions of greenhouse gases. Also, these biologically derived products ("**bioproducts**") are generally less toxic and less persistent than their petrochemical counterparts.

- Groups of companies can mimic the co-operative action of organisms in natural ecosystems by clustering around the processing of a feedstock such as biomass so the by-product of one is the starting material for another. Also, energy, such as waste heat, can be used efficiently. This approach is called "**industrial ecology**".

- The ability to "evolve" bioprocesses and bioproduction systems allows for major improvements in both economic and environmental performance. This permits a manufacturing facility to increase its profitability and capacity while maintaining or even reducing its environmental footprint.

A Note about Bio-safety

The micro-organisms used for industrial bio-processing or for production of industrial enzymes are selected to avoid use of pathogenic organisms. They are subject to stringent environmental regulations in OECD countries. Occupational health regulations also impose rules on their handling in the workplace and, after they are used, they are inactivated by sterilisation. The resulting organic material is usually composted. This breaks down the DNA and protein components and the compost can be used as fertiliser to maintain the level of organic material in the soil.

Examples of Case Studies

The OECD Task Force on Biotechnology for Sustainable Industrial Development has recently published a report entitled "The Application of Biotechnology to Industrial Sustainability". This report provides case studies of how companies in a wide range of industrial sectors have used biotechnology to reduce the cost and environmental impact of their production activities. Summaries of the case studies are provided below.

Fine Chemicals

Given the cost of developing new bio-processes and bioproducts, it is not surprising that some of the first applications of industrial biotechnology appear in the pharmaceutical and fine chemicals segment of the chemical industry, where the value of the products can bear the cost of technology development.

It has long been known that enzymes can catalyse certain chemical reactions with high efficiency and specificity. Since 1970, **Tanabe Seiyaku** (Japan) has used enzymes derived from certain micro-organisms to produce amino acids. Immobilising the enzymes on a surface so they could be used again and again led to 40% cost savings. Improving this system of immobilisation of the micro-organisms to optimise the performance of the enzymes yielded a further 15-fold increase in productivity (*i.e.*, the ratio of product yield to starting material used), resulting in a major reduction of costs and waste.

Enzymes usually function in an aqueous solution and this can reduce the requirement in equivalent conventional chemical processes for organic solvents that will later need to be recycled or disposed of by incineration. **Biochemie** (Germany/Austria), a subsidiary of Novartis, has developed an enzyme-catalysed process for manufacture of the antibiotic cephalosporin. The efficiency of the enzymes was optimised by genetically modifying the micro-organisms that produce the enzymes. When compared to the conventional chemical process, the enzymatic process produces 100 times less waste solvent to be incinerated and, as a result, the cost of production and the potential environmental impact of the process are both reduced.

Metabolic engineering is a technique which involves genetically engineering a micro-organism to contain all the enzyme steps for a series of reactions leading to a particular product and then uses the cell metabolism to drive the reaction. In effect, the cell then becomes a highly efficient mini-reactor for synthesising that product. **Hoffmann La-Roche** (Germany) now uses a metabolically engineered micro-organism to produce vitamin B_2. This has enabled the company to reduce a six-step chemical process to one step. As a result, use of non-renewable raw materials has decreased by 75%, emissions of volatile organic compounds to air and water have decreased by 50% and operating costs have decreased by 50%. Similarly, **DSM** (Netherlands) has used a metabolically engineered micro-organism to reduce the waste produced in the manufacture of cephalexin 3 to7-fold. This has allowed the company to reduce production costs so that it can compete effectively in international markets.

Intermediate Chemicals

Other case studies indicate that, once the underlying biotechnology has been developed and understood, lateral application can occur in other areas. Thus, biotechnologies developed at high cost in the pharmaceutical and fine chemicals segment of the chemical industry can be adapted and applied at lower cost to produce lower value products, such as intermediate chemicals for synthesis of other chemicals or plastics.

S-chloropropionic acid is an intermediate chemical used in the synthesis of certain herbicides. The "S" indicates that the molecule is chiral, that is, one of two asymmetric isomers (the other isomer is the "R" form). The "S" isomer is the one that is biologically active. Conventional chemical procedures for separating chiral molecules are often energy intensive, or require the use of additional chemicals which subsequently require disposal. A biological method for separating chiral molecules involves using a micro-organism that selectively degrades one of the two isomers, leaving the other in essentially pure form once it has been isolated. **Avecia** (United Kingdom) has developed a bioprocess for producing pure S-chloropropionic acid that uses a *Pseudomonas* bacterium to selectively degrade the "R" form. Mutation, selection and adoption of sophisticated means of fermentation resulted in a four-fold increase in productivity, while use of genetic modification to optimise performance even further resulted in an additional five-fold increase in productivity. The bioprocess results not only in lower production costs but also in less waste by-product that requires treatment and disposal.

Mitsubishi Rayon Company (Japan) produces acrylamide, a chemical used to produce acrylic polymers. The conventional chemical process for producing acrylamide from acrylonitrile involves high temperature and the use of either a copper catalyst or sulphuric acid. Mitsubishi Rayon has developed a bioprocess which instead uses a naturally occurring enzyme, nitrile hydratase, to catalyse the conversion of acrylonitrile into acrylamide. The performance and yield of this enzyme has been optimised by genetically engineering the micro-organism which naturally produces the enzyme. The enzyme-catalysed process uses 80% less energy, saves costs and yields higher purity acrylamide than the conventional chemical process.

Polymers

The conventional chemical process for producing certain polyesters involves the use of either a titanium or tin-based catalyst with solvents and inorganic acid at high temperature (200 ^{o}C). **Baxenden Chemicals** (United Kingdom) has developed a bioprocess that uses the enzyme lipase from the yeast *Candida antarctica* to catalyse the polymerisation reaction at a much lower temperature (60 ^{o}C). The lipase gene was transferred into a genetically engineered industrial strain of *E. coli* bacterium to reduce the cost of producing the enzyme. The enzyme-catalysed polymerisation process, when compared with the conventional process, eliminates the use of organic solvents and inorganic acids and yields energy savings of about 2000 megawatts annually at full industrial scale operation. The polymer from the bioprocess also has a more uniform polymer chain length. This results in a melting point over a narrower range of temperature than the conventional polyester, making it more valuable for use as a hot-melt adhesive. Thus, there were both environmental and economic benefits from implementing the enzyme-based bioprocess.

Cargill Dow LLC (United States) has developed polylactic acid (PLA), a biopolymer that not only involves the use of bioprocesses (developed using biotechnology) that are energy and materials efficient but also utilises a renewable agricultural feedstock, corn[4]. PLA is not only recyclable, but also biodegradable, and can be composted. It can functionally replace plastics such as nylon, PET, polyester and polystyrene and life cycle analysis shows that it can do so with a net fossil fuel saving of 20-50% and at a cost which reflects the lower cost of energy and raw material in its manufacture. In the medium term, advances in biotechnology will allow PLA to be produced also from the cellulose found in agricultural and forest by-products. The plastic will then become a net sink for carbon sequestered from the air by crops and trees. Cargill-Dow has constructed a plant in Nebraska, USA, that will produce 140,000 tons of PLA annually.

Food Processing

Often, food processing uses large quantities of water and produces large quantities of organic waste. Biotechnology can help reduce water usage as well as the production of organic waste. For example, **Pasfrost** (Netherlands) has developed a biological treatment system for water in its vegetable processing facility that has reduced water use by 50% and led to significant cost savings. Similarly, **Cereol** (Germany) has implemented an enzyme-based system for the degumming of vegetable oil during purification after extraction. This bioprocess was compared with the conventional degumming process that used sulphuric acid, phosphoric acid, caustic soda and large quantities of water. The enzyme system eliminated the need

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4 . Maize in Europe

for treatment with strong acid and base, reduced water use by 92% and waste sludge by 88% and resulted in an overall cost reduction of 43%.

Fibre Processing

Large quantities of energy, water and chemicals are used to bleach and treat natural fibres for making textiles and paper. Enzymes can help reduce some of these input costs and associated environmental impacts.

For example, **Windel** (Netherlands) uses an enzymatic process to reduce the energy and time required to wash hydrogen peroxide bleach from textiles before dyeing. Use of the enzyme made it possible to reduce the temperature and volume of the second wash from 80-95 ^{o}C to 30-40 ^{o}C, resulting in a 9-14% saving of energy, a 17-18% saving of water and an overall cost saving of 9%. This is very significant in the highly competitive textile industry because margins are generally quite small.

Domtar (Canada) has begun to use the enzyme xylanase, supplied by **Iogen Corporation** (Canada) as an auxiliary brightening agent (this process is called "**bio-bleaching**") for wood pulp in paper making. The enzyme opens up the lignin structure of the wood pulp so that it takes 10-15% less chlorine dioxide to achieve the desired level of brightness. Iogen has reduced the production cost and improved the performance of xylanase by genetically engineering the fungus from which it is extracted. The use of xylanase has helped Domtar reduce the amount of organically bound chlorine in waste water by 60% and the cost of bleaching chemicals by 10-15%. **Oji Paper** (Japan) has also used xylanase to achieve similar reductions in the requirement for bleaching chemicals and in levels of organically bound chlorine in its waste water. In addition, it produces its own xylanase on-site by fermentation so its input costs are reduced even further.

Mining and Metal Refining

Billeton (South Africa) has developed a bioprocess ("**bio-leaching**") to liberate copper from sulphide ore. The bioprocess uses naturally occurring bacteria to oxidise the sulphur and iron present in the ore at ambient temperature. The conventional process for isolating the copper from the ore involves transporting the mined ore to a smelter where the impurities are driven off at high temperature. The bio-leaching process is carried out at the mine site. This saves the cost and energy required to transport the ore and also eliminates the emission of large quantities of sulphur oxides, arsenic and other toxic metals into the atmosphere by the high temperature roasting process. After the copper is extracted from the acidic leach water, the waste water is neutralised and toxic substances such as arsenic are immobilised in a stable form stored at the mine site. The bio-leaching process can be used to process low-grade ores and arsenic-containing ores that could not be processed effectively by high temperature smelting. The capital cost requirements of the bio-leaching process are 25% less than for building a smelter. Bio-leaching currently accounts for 20-25% of world copper production.

Budel Zinc (Netherlands) is a major producer of zinc. The acidic waste water from its zinc refinery contains zinc and other metals (tin, copper, nickel, manganese, chromium, lead and iron). The conventional process for treating this waste water involves neutralising it with lime or limestone, which results in large quantities of gypsum contaminated with heavy metals. Budel has developed a bioprocess that uses sulphate-reducing bacteria to capture and recycle zinc and other metals in its waste water as metal sulphide precipitate. The metal sulphide precipitate is recycled back into the refinery feedstock. This process has resulted in a 10 to 40-fold decrease in the concentration of heavy metals in the refinery wastewater and eliminated the production of metal-contaminated gypsum which is a hazardous solid waste by-product.

Energy

Examples of biotechnology applications in the energy sector occur in both the conventional fossil-fuel and the renewable energy segments of the industry.

Conventional fossil-fuels are usually extracted from deposits buried below the surface of the earth. Drilling of oil wells requires the use of substances called drilling fluids or drilling mud. These substances help lubricate the drill and its pipe as well as hold open the well bore. Drilling fluids are designed to deposit a low permeability layer on the surface of the borehole to limit leakage of the drilling fluid into the oil-bearing formation and to prevent invasion of solids into the oil production zones. Once the well is drilled to the desired depth, the low permeability layer must be removed in order to maximise oil production rates. Traditional drilling fluids are muds – dispersions of clay minerals in water and oil where the clay provides the required viscosity and the oil provides the lubrication. These muds pose two problems: (*i*) the oil used in their formulation can have negative environmental impacts and requires treatment (*ii*) the strong acid required to remove the low permeability layer is toxic to the environment, corrodes equipment and does not uniformly remove the low permeability layer.

M-I and **British Petroleum Exploration** (United Kingdom) are now using a drilling fluid containing mixtures of bio-organic polymers such as xanthan gum, which provides viscosity, and starch or cellulose, which acts as a binder. The formulation also contains an inert solid called a bridging agent that has a particle size allowing it to bridge pores in the structure of the rock being drilled. This formulation is non-toxic and avoids the problems of conventional drilling muds: (*i*) there is no oil or other component which requires treatment before release into the environment; and, (*ii*) the enzymes used in removing the low permeability layer not only perform better but also do not corrode equipment or pose environmental hazard.

Biotechnology has been used to optimise the characteristics of these enzymes (cellulase, hemicellulase, amylase and pectinase) to work under the conditions found in a borehole. Although the use of bio-organic drilling fluid systems is in its early days, it appears in a number of cases that their performance is satisfactory and permit cost savings of USD 75 000 – 83 000 per well drilled.

Ethanol is one renewable fuel whose production is increasing rapidly in response to the need for transportation fuels that produce lower net emissions of greenhouse gases (GHG). Ethanol is produced by fermentation of sugars (such as glucose) using brewers' yeast. The sugar can come from cornstarch. It takes considerable energy to produce corn, however, so the net reduction in GHG emissions is around 40-50% when ethanol from corn is used to replace gasoline (petrol). If wood cellulose and waste materials are used as the source of sugar to produce ethanol, the net reduction in GHG emissions is larger, around 60-70%. Therefore cellulose-containing materials are, from a GHG perspective, the material of choice for producing ethanol. However, the lignin in woody plant material can prevent full conversion of cellulose into fermentable sugar. **Iogen Corporation** (Canada) has developed a process utilising cellulase enzymes that maximise the conversion of cellulose into fermentable sugar. The yield and activity of the cellulase enzymes has been optimised using biotechnology. Iogen is in the scale-up phase of the technology and indications are that the cost of ethanol produced in this manner will be competitive with the cost of gasoline produced from oil costing USD 25 per barrel.

Lessons from the Case Studies

It is possible to draw a number of general conclusions from the case studies:

i. The application of biotechnology in a wide range of industry sectors (chemicals, plastics, food processing, natural fibre processing, mining and energy) has invariably led to both economic and environmental benefits via processes that are less costly and more environmentally friendly than the conventional processes they replace. In effect, the application of biotechnology has contributed to an uncoupling of economic growth from environmental impacts.

ii. The application of biotechnology to increase the eco-efficiency of industrial products and processes can provide a basis for moving a broad range of industries toward more sustainable production. To achieve this, further development of biotechnology and supporting technologies will be needed, as well as policies that provide incentives for achieving more sustainable production.

iii. The main driving forces for adoption of more efficient bioprocesses and bioproducts are cost savings and improved product quality/performance. Environmental considerations were (in the case studies, at least) an important but secondary driving force.

iv. Successful biotechnology/bioprocess development requires effective management of technology development by companies and use of tools that assess both the economic and environmental performance of technology during its development. There is a need for improved assessment tools that are easier to use and at earlier stages of the technology development process.

v. Even large companies may not have in-house all the expertise required to develop more efficient bioproducts and bioprocesses. Collaboration with university and government researchers and other companies is an important contributing factor for successful introduction of these products and processes.

vi. Long lead times are often required for introduction of ‘paradigm shift’ technology into a company; but development times can be reduced considerably in subsequent development cycles.

vii. The application of biotechnology for developing industrial products and processes is still in its infancy. As awareness builds and the technology continues to be developed and diffused through different industry sectors over the next few decades, the economic and environmental benefits are predicted to grow.

Setting a Path to a Sustainable Future – The Bio-based Economy

The case studies outlined above show that biotechnology is an effective tool which provides a means of reconciling the need for economic growth with the need for environmental protection. The eco-efficiency of industrial bioproducts and bioprocesses can provide a basis for moving a broad range of industries toward more sustainable production.

However, these applications are occurring as a "thousand points of light", that is, without a guiding principle or a strategic orientation. Such a strategic orientation is needed to avoid investing resources on incremental improvements in the cleanliness of industrial production systems which may never make it to "clean enough", *i.e.* sustainable. Shifting toward an economy more extensively based on renewable raw materials – a bio-based economy[5] – does provide such an integrating principle.

As can be seen in Table 1, continued use of conventional processes that are not eco-efficient in combination with non-renewable feedstocks results in continued pollution and exhaustion of resources. If conventional processes that are not eco-efficient are used in combination with renewable resources, they may lead to depletion of the renewable resource as the global economy grows and demand increases. If cleaner production processes are used on non-renewable resources they will extend the lifetime of those resources, but only postpone their inevitable exhaustion. Sustainability is most likely to be found in utilising renewable resources through cleaner processes that are eco-efficient.

Table 1

Choice of Process and Feedstock – Implications for Sustainability

	Conventional Processes	Cleaner Processes
Non-renewable Feedstock	Status quo – pollution; rapid exhaustion of resources	Extended life of resources – "postponing the inevitable"
Renewable Feedstock (*e.g.* biomass)	Depletion of renewable resources	Best chance for sustainability

Developing a sustainable economy more extensively based on renewable carbon and eco-efficient bioprocesses (a 'bio-based economy') is one of the key strategic challenges for the 21st century.

At present, the global economy depends to a large extent on energy, chemicals and materials derived from fossil carbon sources, mainly petroleum. Petroleum provides us with fuels for transportation and heating. It also yields synthetic chemicals for producing plastics, paints, dyes, adhesives and a wide range of other useful industrial and consumer products. These developments have contributed to strong economic growth and employment and have literally transformed our global society. But this has come at a cost. The Petrochemical Age has also resulted in massive pollution of air, water and soil as well as emissions of greenhouse gases responsible for climate change. Petroleum is also a finite, diminishing

5 The bio-based economy uses renewable bio-resources (agricultural, forestry and marine) and eco-efficient processes (including bioprocesses) to produce sustainable bioproducts, jobs and income.

resource now subject to strong price increases and fluctuations. The present level of global energy consumption, production and industrial growth is ultimately not sustainable because it is only made possible by continued withdrawals from the stored “bank” of fossil carbon which is finite and not renewable.

The world was not always dependent on petroleum. A traditional bio-based economy provided and continues to provide us with food, feed, fibre and wood. Before the 1920s, many of our industrial products were also bioproducts, such as fuels, chemicals and materials derived from biomass, primarily wood, and various agricultural crops. Cheap and abundant oil changed that. However, as seen in the case studies outlined above, advances in technology, and biotechnology in particular, are making it economically viable and environmentally attractive to "go back to the future" and begin supplementing, and eventually perhaps, replacing petroleum with biomass, a renewable feedstock derived mostly from plants.

Improved understanding of biodiversity, ecology, biology and biotechnology is making it possible both sustainably to increase biomass productivity in forestry and agriculture as well as to utilise that biomass and waste organic materials in a highly efficient and sustainable manner. Without such advances in science and technology, the move to a bio-based economy would result in rapid depletion of renewable resources and environmental degradation. Thus, advances in science and technology are making it possible to have an economy where industrial development and job creation are not in opposition to environmental protection and quality of life. Getting there will be a major challenge, requiring effective tools to assess technology, processes and products for sustainability and also policies that encourage sustainable production and consumption.

The life sciences, and in particular biotechnology, will play a prominent role in meeting that challenge. For example, the Vision[6] and Technology Roadmap[7] for Plant/Crop Based Renewable Resources 2020 provide a view of how this can be conceived, planned and executed through targeting the development of technologies in the near, medium and long term for:

- Selecting and developing value-added crop and tree varieties for conventional and industrial applications.
- High-yield, sustainable crop and tree production.
- Eco-efficient harvesting and processing.
- Sustainable utilisation of the resulting products.
- Closing the loop back to the environment to maintain soil organic content and fertility.

The “bio-based economy” offers hope both for developed and developing countries. For developed countries, it presents the opportunity to use their technological capabilities for national energy security to head off major economic and social disruptions which will be caused by fluctuations in the availability and price of energy and petrochemicals as the supply of these finite, non-renewable resources continues to diminish. It will also help them diversify and grow employment in their rural economies.

6 US Department of Energy (1998), Vision for Plant/Crop Based Renewable Resources 2020. Web site: www.oit.doe.gov/agriculture/pdfs/vision2020.pdf.

7 . US Department of Energy (1999), The Technology Roadmap for Plant/Crop Based Renewable Resources 2020. Web site: www.oit.doe.gov/agriculture/pdfs/ag25945.pdf.

For a number of developing countries, it provides the potential to leapfrog (at least in part) the age of fossil-fuels and petrochemicals to the age of biofuels and biochemicals. These are less toxic and more easily biodegradable than their petrochemical counterparts and can be derived from locally grown feedstock, leading to local self-sufficiency, an improved economy and a better quality of life.

However, if we are to see a move to such a future in the 21^{st} Century then, despite the potential economic, environmental and social benefits, it is not realistic to assume that a new "green revolution" will sweep spontaneously over existing industries. Potentially, the move to a bio-based economy could be at least as big as that caused by the development of the petrochemical age during the 20^{th} Century. But societal values are different in 2001 from those of 1901. The transition therefore will need to be carefully managed, not least because it will link such issues as biotechnology and GMOs, preservation of biodiversity, climate change, globalisation, economic growth, sustainable development and quality of life.

The interplay of these issues could pose complex problems and policy issues for governments, industry and civil society as they try to optimise economic, environmental and societal benefits, while enabling and fostering the development of a bio-based economy in their countries. Visionary thinking is required among stakeholders if we are to identify proactively the key issues and policy decisions that will have to be dealt with along the way. Further work on these issues is under way in a number of countries as well as in a number of international fora including the OECD, UNCTAD and UNEP.