# The Concept of Clean Technology

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## ABSTRACT

**Clean Technology** goes beyond **Clean-Up** (or "End of pipe) Technologies to include **pollution prevention, waste minimisation,** and **cleaner production.** However, the concept of Clean Technology goes deeper than changes in technology, to ways in which human needs can be satisfied sustainably. In other words, Clean Technology, concentrates on delivering a human benefit rather than making a product. Introducing cleaner technology may therefore involve new commercial relationships as well as new technological practices. In some economic sectors, this involves leasing or providing a service rather than selling a product

**Life Cycle Assessment (LCA)** is an important tool in Clean Technology. LCA involves determining all the resources used and all the wastes and emissions produced in providing the human benefit. Use of LCA ensures that improved environmental performance in one part of the Life Cycle is not achieved merely at the expense of more environmental damage elsewhere. Going beyond LCA, the concepts of **Life Cycle Design** and **"metabolised" use of materials** are approaches to obtain maximum benefit from materials as they pass through the human economy. **"Closed-loop"** use can be a component of clean technology. Looking beyond simple re-use and recycling, a material may pass through a **"cascade of uses"**. typically a series of applications with progressively lower performance specifications. Closed-loop use necessarily involves a change in commercial practice, because the material or product must be recovered after use.

## INTRODUCTION

Over roughly the last five years, the UK Engineering and Physical Sciences Research Council has been developing a program of fundamental and strategic research in Clean Technology. In order to guide this programme, it was necessary to develop a working definition of this new concept, and to explore how Clean Technologies can be introduced in practice. This paper summarises the underlying thinking about the nature and use of Clean Technology.

Clean Technology is seen as an essential way to achieve sustainability-i.e. human life which can continue on earth indefinitely. This aspect of sustainability is summarised in Figure 1. At the heart of the system in Figure 1 is human society (which gives rise to its own direct emissions to the environment, E). Human needs are supplied by agricultural and industrial activities (plus some products derived from natural ecosystems). Agriculture provides food and other materials and generates its own environmental emission, E, and wastes. Part of the energy input to agriculture comes from the sun, but it also uses substantial energy inputs derived from non-renewable fossil fuels [1]. At present, industrial activity is powered primarily by non-renewable energy. Much of the waste from human society and from agricultural and industrial activities can be re-used in some way, but some remains as residues which are not currently used. However, these residues do not leave the planet-in thermodynamic terms, the earth is a closed system.

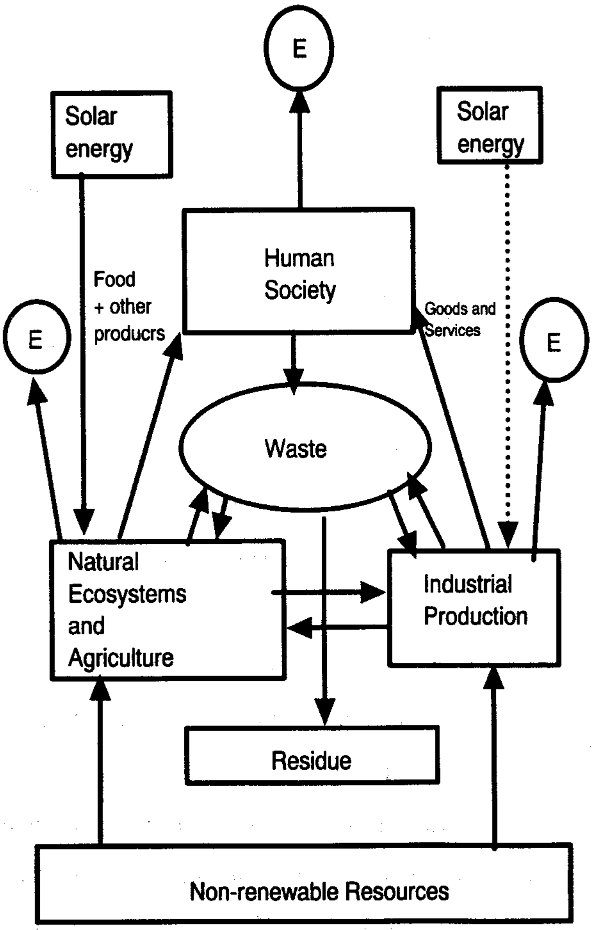

Fig. 1 Schematic system representation of human activities on earth; E=emission

In the most general terms, Clean Technology is concerned with obtaining maximum human benefit from the material and energy flows summarised in Figure 1. By definition, non-renewable energy sources are not sustainable. Therefore, an important long-term challenge for sustainability is to switch from non-renewable to renewable energy sources.

## WHAT IS CLEAN TECHNOLOGY

Clean Technology is not a set of "hard technologies"- it is really a way of thinking. The Figure shows the trade-off between Clean Technology and Clean-Up Technology. The Figure shows the trade-off between economic and environmental costs in providing some human service. To take a specific example, this might be a unit of electrical energy distributed via a grid. Curve 1 represents an existing technological approach to supply the service. For electrical energy, it might represent generation by coal combustion. Point A represents current industrial practice. In the face of legislative or social pressure to reduce environmental impact, it is possible to modify the plant. However, modification of retrofitting always involves economic cost. Thus the change associated with clean-up technology corresponds to the shift from A to B in Figure 2. In the specific example of electricity generation from coal, this might correspond to reducing acid gas emissions by flue gas scrubbing. This is an example of "end of pipe" pollution abatement.

An alternative to modifying the existing technology is to look for a different way to provide the service, which reduces both economic and environmental cost. This different technology is represented by curve 2 in Figure 2. If such a technology can be found or developed, it is possible to shift from A to C, achieving both environmental improvement and economic advantage. Such a shift represents introducing a Cleaner Technology. For the example of electric power generation from coal, the Clean Technology shift would be illustrated by changing from combustion to Integrated Gasification and Combined Cycle (IGCC) plant. Because the efficiency of energy conversion is higher, the operation cost per unit of electrical energy delivered is reduced. Because many of the emissions (including acid gases and greenhouse warming agents) are reduced, the environmental "cost" is also reduced.

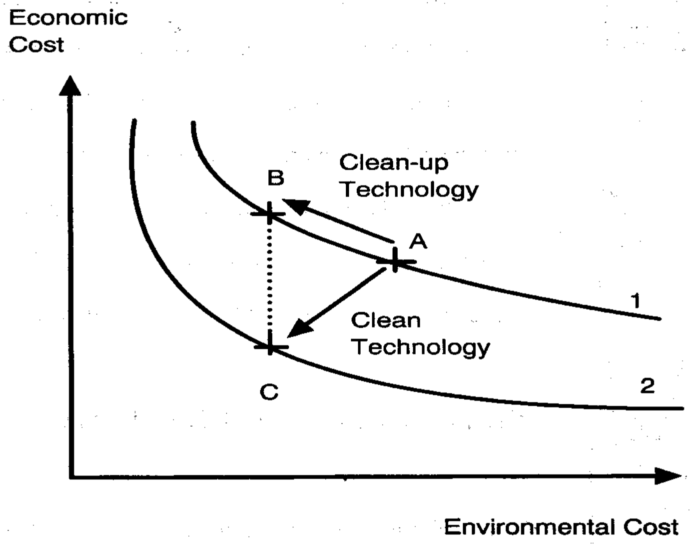

Fig. 2 Distinction between Clean Technology and Clean-up Technology [2]

This thinking leads to the definition of Clean Technology underlying the UK research programme [3];

A Clean Technology is a means of providing a human benefit which, overall, uses less resources and causes less environmental damage than alternative means with which it is economically competitive.

The word "overall" has a particular significance which is explained later in this paper.

Introduction of Clean Technology concepts into coal conversion also serves to illustrate one of the most important barriers to the take-up of Clean Technology. The shift from point A to point C in Figure 1 may entail development and investment in the new technology -as in changing from coal combustion to IGCC. Therefore the rate of introduction of clean technology may be limited by the rate of replacement of capital plant. This is also the reason why many organisations first encounter Clean Technology by implementing waste reduction programmes [4]. It is common experience that waste reduction at source leads to reduced cost as well as reduced environmental impact [5], so that it does represent an embodiment of

Clean Technology. However, a waste minimisation programme is relatively cheap and usually involves no major investment. Therefore the barrier to implementation is reduced or removed.

Social pressures for environmental improvements, expressed through environmental legislation, lead naturally to technological change. This is illustrated schematically by Figure 3. If expectations of environmental performance are low, as at point B, then the technology represented by curve 1 is appropriate. Improvements in environmental performance correspond to a shift to the left on the diagram, until point A is reached. Further improvement, for example to point C, can best be achieved by shifting to the cleaner technology represented by curve 2.

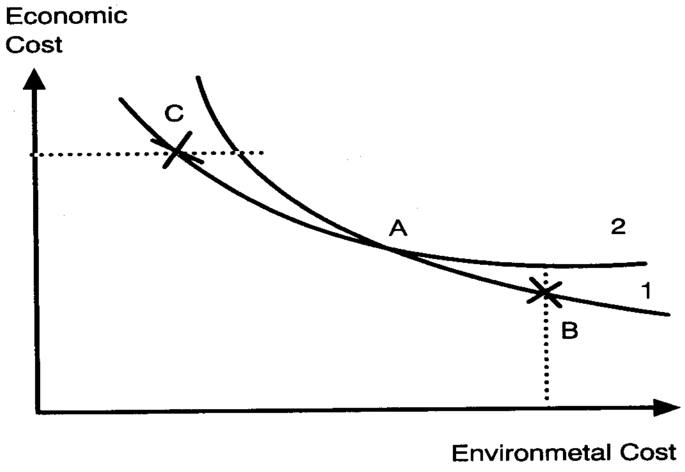

Fig. 3 Environmental performance as a "driver" for technological change [3]

Pursuing the implications of environmental performance further, it is possible to conceive or an environmental learning curve, as shown schematically in Figure 4. The Figure is intended to be analogous to the familiar "Boston learning curve". The idea is that the environmental cost reduced steadily with experience, represented by the total number of "functional units" of the service (see below) which have been delivered. This continual environmental improvement can result from periods of incremental improvement, punctuated by qualitative changes in technology, consistent with Figure 3.

Two qualification must be noted in connection with Figures 2 to 4.

"Economic cost" means the conventional "internal" cost of providing the human benefit; so-called" external costs", (i.e. the monetarised costs of environmental damage) are not included [2]. Furthermore, environmental costs cannot really be represented by a single parameter, because environmental impact includes a number of distinct and incommensurate environmental effect. Thus Figures 2 to 4 are schematic only. However, analytical techniques are being developed [e.g. 6] to incorporate multiple variables into strategic environmental decisions.

## HOW CLEAN IS A TECHNOLOGY?

Even recognising that environmental "cost" cannot be expressed by a single parameter, there

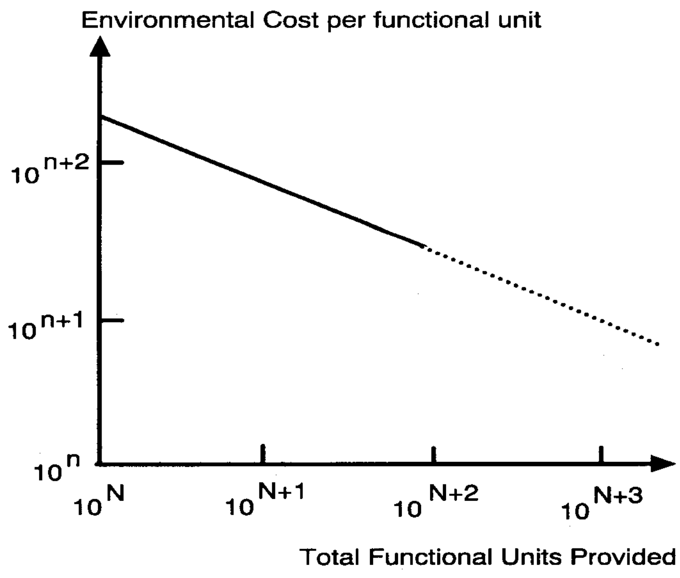

Fig. 4 An environmental learning curve

remains the problem of assessing the total environmental impact associated with delivering the service. The United Nations Environment Programme defines Cleaner Production [7] as:

> a conceptual and procedural approach to production that demands all phases of the life-cycle of a product or process should be addressed with the objective of prevention or minimisation of short-and long-term risks to human health and to the environment

Cleaner Production is more restricted in concept than Clean Technology, because it focuses on the product rather than the function. However, the definition is significant because it focuses on the product rather than the function. However, the definition is significant because it emphasises the need to assess the whole life cycle. The reference to overall resource use and environmental damage in the definition of Clean Technology given earlier carries the same implication. Thus Clean Technology is unavoidably linked to Life Cycle Assessment, as the tool for assessing how clean is a technology or a product or a process.

Life Cycle Assessment is a formal procedure defined[8] as a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extraction and processing of the raw materials; manufacturing, transport and distribution, use, re-use, maintenance; recycling and final disposal.

We concentrate here on the first part of this process; evaluating the environmental burdens. This part of a Life Cycle Assessment (LCA) includes:

**Goal Definition** : defining the system boundary and the "functional unit" on which the assessment is to be based;

**Inventory** : quantifying the flows which cross the system boundary.

The approach is shown schematically by Figure 5. The centre of the Figure represents an economic system which produces outputs of goods and services. For assessing Clean Technology, we concentrate on the output of services. So far as possible, material products are treated as part of the economic system, not as outputs [10, 11]; this is discussed further below. The system boundary represents the distinction between **the economic system** and **the environment.** Thus the word "environment" is used here in its original thermodynamic sense, as "that which surrounds the system under study" [12].

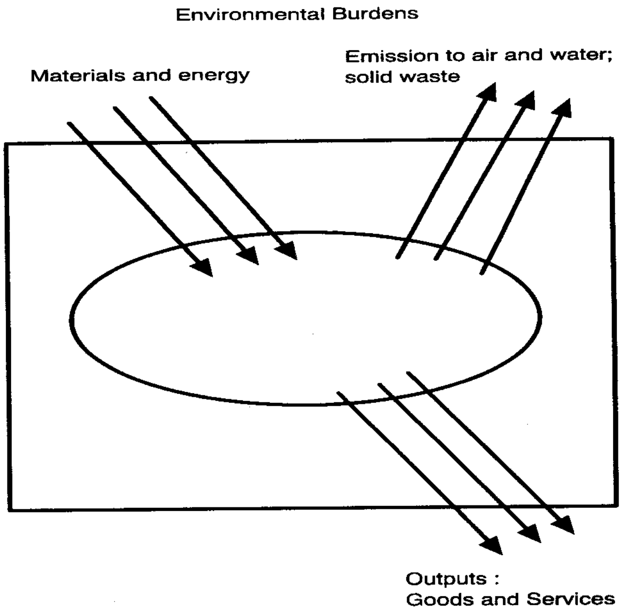

Fig. 5 The basis of environmental system analysis [9]

In order to deliver the functional outputs, the system requires inputs of energy and materials, derived originally from primary resources as in Figure 1. The materials eventually leave the economic system as emissions to air and water and as solid residues or wastes. The total set of resources used, emissions and residues are sometimes called **the environmental burdens** associated with the economic system.

One of the particular characteristics of Life Cycle Assessment lies in the way the system boundary is defined, as part of the Goal Definition stage. This illustrated by Figure 6. Conventional process analysis and environmental impact assessment concentrate on a process or manufacturing facility. Thus they use a system boundary represented by 1 in Figure 6. The concept of Integrated Pollution Control (IPC), developed in the UK by Her Majesty's Inspectorate of Pollution, basically considers the flows across boundary 1 to evaluate the wastes and emissions from the process. The principle of IPC is to ensure that one form of emission is not merely abated by increasing another emission or waste.

LCA goes further than IPC. A product does not leave the earth simply because it has been sold. To give an example, detergent manufacture in the UK is subject to IPC, to ensure that the emissions to air and water are strictly limited. However, the detergent product is then packaged, sold and discharged to the water system by the user! This cannot be a clean technology. Life Cycle thinking shows that it is as important to consider the way the detergent is used as to regulate emissions from manufacture. In a parallel analysis Life Cycle Assessment of domestic washing machines also shows that it is as important to consider the way the detergent is used as to regulate emissions from manufacture. In a parallel analysis, Life Cycle Assessment of domestic washing machines also shows that their greatest environment burdens are associated with the use "phase" of the life cycle, with the burdens from manufacture, distribution and disposal negligible by comparison [13]. This realisation has driven the development in recent years of concentrated detergents which work in cold water. Going beyond what amounts to the waste minimisation approach, it is possible to develop (at least in concept) clean technology approaches to delivering the function "cleaning soiled clothes" [see 2].

In general, the product may be recovered and recycled after use, or it may be used for some other function (see below)/ Eventually it leaves the system as waste or emissions : W in Figure 6. Similarly, the materials used in processing or manufacture derive originally from primary resources, which must be extracted and processed before they become feedstock.

Furthermore, all these operations use energy, which derives from primary resources - usually, as in Figure 1, fossil fuels. Energy conversion generated its own emissions and residues. Following the clean technology emphasis on benefit rather than product, the purpose of the economic system in Figure 6 is to deliver the use function. Alternative systems are therefore compared on the basis of the service which they deliver. In LCA, the basis for comparison is termed **the Functional Unit.** For example, alternative packaging materials are compared on the basis of the quantity of material packaged, not on the quantity of packaging material itself.

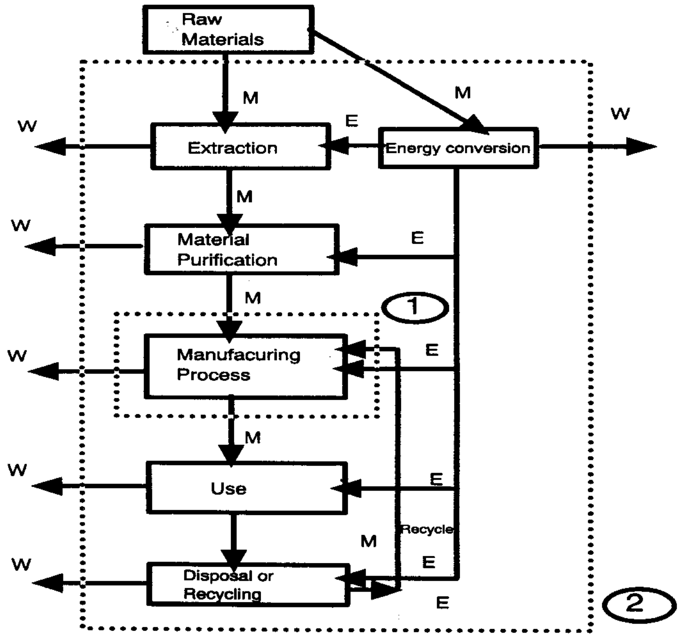

Fig. 6 System boundaries used in environmental system analysis [3];
1. Process Analysis or Environmental Impact Assessment;
2. Life Cycle Assessment;
M- Material Flow;
E-Flow of energy (or fuel)
W-Waste or emission.

To consider the whole life cycle of the energy and material flows used to deliver the use, it is essential to consider the whole system within boundary 2 in Figure 6. Life Cycle Inventory(LCI) identifies and quantifies the flows across this broader system boundary, i.e. the environmental burdens. A Full Life Cycle Assessment assesses the environmental impacts of these environmental burdens.

Much of the work on LCA has concentrated on individual products to identify the stages in their life cycle where burdens can best be reduced [4], or to compare products which deliver the same function as a basis for establishing criteria for Ecolabelling [15]. However, promising areas for future applications are as a design tool for products [16] and processes [6] and for policy assessment [10]. To give a simple example of the application of LCA to process design, scrubbing with caustic soda (i.e. sodium hydroxide solution) is sometimes used to remove nitrogen oxides from gases before they are emitted to the atmosphere. At first sight, this appears to be an example of a clean-up technology. However, referring to the associated life cycle, the caustic soda must be made, by electrolyzing sodium chloride and transported to the point of use. LCA calculations show that the nitrogen oxide emissions from transport and from generation the electrical power used in brine electrolysis can exceed the quantities of nitrogen oxides collected in the scrubbing process [17]. Thus what appeared to be a clean-up technology proves to increase total environmental damage. This is a case where Clean Technology is clearly needed, to convert the nitrogen oxides at or close to their source or to redesign or eliminate the process which gives rise to them.

## INDUSTRIAL ECOLOGY AND LIFE CYCLE DESIGN

Life Cycle Assessment is basically a decision-support tool. Its systematic application to product design - Life Cycle Design - is becoming accepted as a tool for reducing the environmental impact of manufactured goods. Life Cycle Design is rapidly achieving acceptance in the electronic, automobile, domestic "white goods" and office equipment sectors.

Photocopiers provide an informative example [2]. Some 80% of the photocopiers in use worldwide are leased rather than sold. Thus the industry is already accustomed to providing the function of copying documents rather than selling machines. In particular, it is already commonplace for the product which delivers the function to be returned to the supplier at the end of its service life. Allowing for re-use of components and recycling of materials, typically only some 2% of the mass of a photocopier becomes solid waste[2].

This example introduces some of the key issues in going beyond Life Cycle Design to apply Clean Technology thinking :

1. Responsibility for the product after use must be defined. The **Responsible Care** approach adopted by the chemical industry embodies this idea. A further example is the **Take-Back** approach being discussed in some manufacturing industries, whereby the product is returned to the manufacturer or an approved agent after use. Under Take-Back regulations, the difference between selling and leasing becomes indistinct- effect, it is a move towards the leasing arrangements with which the photocopier industry is already familiar.

2. Products should ideally be designed for re-use or recycling, and for extended service life. One of the problems in extending service life is that the product must be designed so that it can be upgraded to incorporate technological improvements. The latter requirement is illustrated by the example of domestic washing machines, discussed earlier. Given that most of the environmental

burdens arise from use, improvements in performance may be more important than extending service life. The thrust of these developments is towards **dematerialisation of the economy,** so that human benefits are delivered without consuming resources[18, 19]. Other implications of the shift towards a service economy are discussed later in this article.

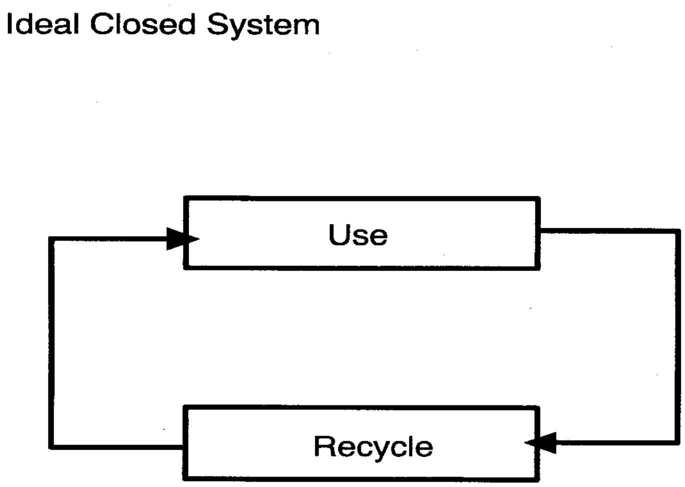

Fig. 7 Idealised closed-loop recycling

Clean technology combined with life cycle thinking leads to an approach which goes beyond the conventional hierarchy "Reduce-Re-use-Recycle". We start by recognising that re-using or recycling a product is not the simple closed-loop operation illustrated by Figure 7. in reality, inputs of energy and materials are required, leading to wastes and emissions, while some of the material inevitably becomes degraded and leaves the loop. Thus the reality of recycling is the general system shown in Figure 8.

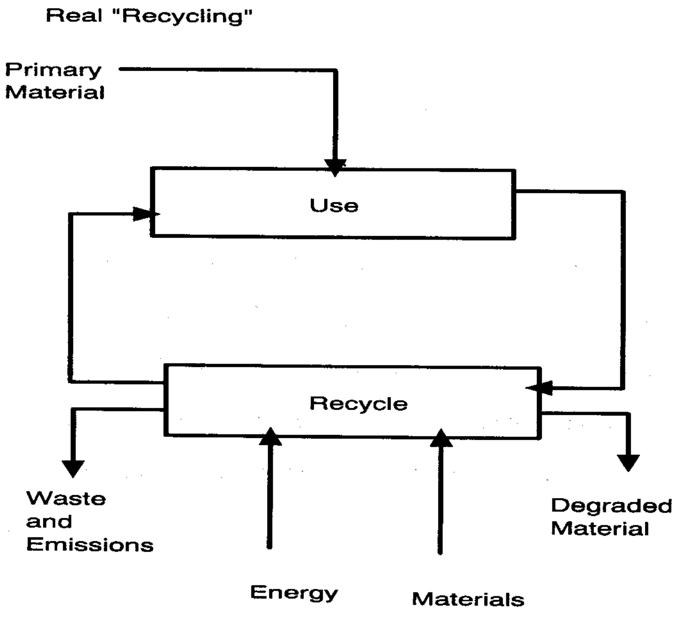

Fig. 8 Real recycling

Life Cycle Assessment can be applied to determine whether recycling really is the best option for waste management, by balancing the burdens associated with recycling against the burdens avoided by the material recovery [e.g. 10, 20].

The degrade or non-recycled material leaving the loop in Figure 8 should not be treated as waste which leaves the economic system; i.e. it is not merely an environmental burden. It may be usable elsewhere. Thus a material may pass through a series of applications, as shown schematically in Figure 9. Typically, the successive applications are associated with progressively decreasing performance specifications, so that this system is sometimes called **a cascade**

**of uses** [19, 21].

Cascaded use is already established for some metals, notably aluminium. However, cascaded use of polymeric materials is still at a preliminary stage.

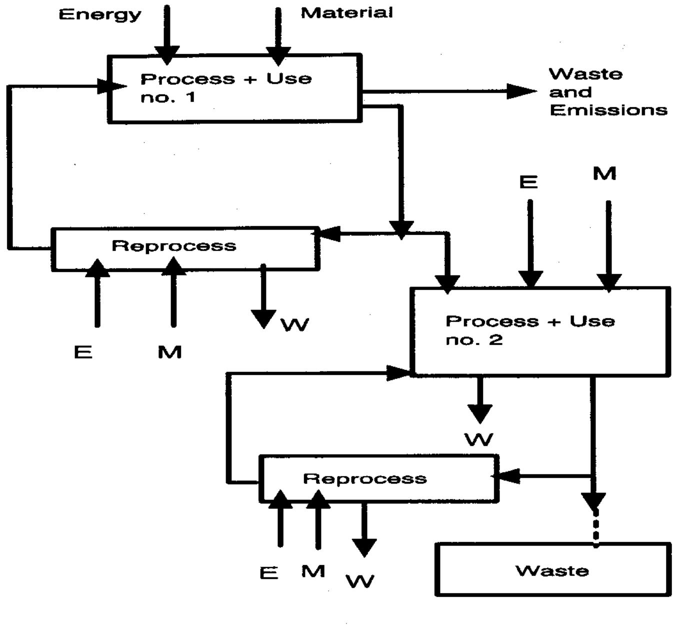

Fig. 9 Metabolised use of a material through a cascade of uses[21]

The application of Life Cycle Design thinking must now extend to planning the overall use of the material, to avoid the use of additives (such as pigments or plasticisers) at one stage which inhibit subsequent applications. Organic materials can be used as fuels. Therefore the last cycle of use of a polymer will normally be as a fuel [21]. This aspect of **Clean Technology** is sometimes described as **Industrial Ecology**, with the objective of achieving **metabolised use of materials.**

## CHANGING COMMERCIAL RELATIONSHIPS

A simple but instructive example of industrial ecology is provided by the practices which have been introduced in Britain in the use of organic solvents and lubricants. This case study is discussed in more detail by Clift and Longley[2]. The first step was a change from simply selling the material to taking it back after use in fact, changing from selling the product to leasing its use. This essential Clean Technology step depended on redefinition of the business rather than any technological change. The reduced solvent was reprocessed, and re-used. The result was reduced solvent losses (i.e. reduced environmental "cost") and also greater economic efficiency. Thus the change is correctly described as introduction of Clean Technology, in the sense of Figure 2.

The residue from reprocessing cannot be returned to the original use as solvent or lubricant. However, it can be used in other ways, so that its passage through the human economy represents a cascade of uses as in Figure 9. In the UK, residues are blended to provide specification fuels which can be used, for example, to fire cement kilns.1)

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1) Although this approach is simple and logical, it has been opposed by some groups who are unconvinced or ignorant of the overall life cycle benefits

More radical applications of the Clean Technology approach are starting to emerge in the agrochemical industry. Simple calculations [2, 22] show, for example, that the quantities of pesticides applied to crops are many orders of magnitude more than the quantities actually needed to kill the unwanted seedlings - perhaps as much as $10^9$ times higher. Even without a formal Life Cycle Assessment, it is clear that the use of Clean Technology in agriculture must include targeted application of small quantities of very specific herbicides and pesticides.

The general tend towards progressively lower application rates of agrochemical is consistent with Figure 4. As illustrated by Figure 3, significant changes in technology and commercial practice will be needed to sustain this continual improvement in environmental performance. In the UK, work is already in progress to develop robotic devices to detect areas of high pest or weed populations for selective application pesticides or herbicides. Future agrochemical will be even more specific in their biological effects, with shorter lives once they are released into the natural environment. This is leading in turn to new techniques for purification of agrochemicals. At present, chemicals are separated and purified by physical property, using techniques such as distillation and extraction. For highly active and specific biological agents, this approach is inappropriate. Instead, agrochemicals may be purified according to their specific biological activity. This suggests the use of techniques adapted from the pharmaceutical sector, relying on specific adsorption. Generically, this kind of process is known as **affinity separation**. It uses, for example, an antibody immobilised by covalent binding to a solid support phase. The antibody "recognises" the biological activity of its antigen, and thus selectively recovers molecules with that biological action from a complex mixture.

Looking beyond these technological changes, to reduce application rates by orders of magnitude will require a shift in commercial relationships in the agrochemicals sector, mirroring shifts in other sectors where Clean Technology ideas have been implemented. The shift will be away from selling agrochemicals towards providing the service of managing the crop.

## CONCLUSIONS

Clean Technology is an essential component in moving towards sustainable human activity on earth. Clean Technology is more of a way of thinking than a set of "hard" technologies. Clean Technology concentrates on the most efficient way to deliver services rather than to ,make products. As a result, Clean Technology leads to competitive economic advantage as well as to improved environmental performance. Life Cycle Assessment is an essential component of clean technology thinking, going beyond environmental design and recycling to the Industrial Ecology approach of metabolising the use of materials within the human economy.

## REFERENCES

1. Cowell, S. J. and Clift, R., (1995). ***"Life Cycle Assessment of Food Production Systems"***, Proceedings of International Conference of The Fertiliser Society, Cambridge, 6-8 December

2. Clift, R. and Longley, A. J., (1995) ***"Introduction to Clean Technology"***, Chapter 6 in Clean Technolgy and the Environment, ed. R.C. Kirkwood and A. J. Longley, Blackie Academic & Professional, Glasgow (UK).

3. Clift, R., (1995) ***"Clean Technology-An Introduction"***, J. Chem. Tech. and Biotech. 62, 321-326.

4. Christie, L., and Rolfe, H. (1995) ***"Cleaner Production in Industry"***, Policy Studies Institute, London

5. Crittenden, B. D. and Kolaczkowski, S. I., (1992) ***"Waste Minimisation Guide"***, Institution of Chemical Engineers, Rugby(GB).

6. Azapagic, A. and Clift, R., (1995) ***"Life Cycle Assessment and Linear Programming - Environmental Optimisation of Product System"***, **Computers in Chemical Engineering** 19, Suppl. pp S229-S234.

7. Bass, L., Hoffman, H., Huisingh, J., Koppert, P., and Neuman, F. (1990) ***"Protection of the North Sea; Time for Clean Production"***, Erasmus University, Rotterdam(NL).

8. SETAC (Society of Environmental Toxicology and Chemistry) 1993 ***"Guidelines for Life-Cycle Assessment; 'A code of Practice'"***, SETAC, Brussels (B) and Pensacola (USA).

9. Azapagic, A. and Cliff, R. (1994) ***"Allocation of Environmental Burdens by Whole System Modeling - the use of linear programming"***, pp. 54-60 in **Proceedings of the European Workshop on Allocation in LCA.** ed. G. Huppes and F. Schneider, Centre of Environmental Science, University of Leiden (NL).

10. Doig, A., Clift, R. and others (1995) ***"Life Cycle Inventory for Waste Management"***, Dept. of the Environment (GB)

11. White, P. R., Franke, M. and Hindle, P. (1995) ***"Integrated Solid Waste Management -a Life Cycle Inventory"***, Blackie Academic and Professional, Glasgow (GB).

12. Clift, R., Burningham, K., and Lofstedt, R. E. (1995) ***"Environment - A Social Science Perspective,"*** ed. Y. Guerrier, N. Alexander, J. Chase and M. O'Brein, John Wiley and Sons, Chichester (GB)

13. UK Ecolabelling Board (1992) ***"Ecolabelling Criteria for Washing Machines"***, UKEB, London.

14. Heijungs, R., ed. (1992) ***"Environmental Life Cycle Assessment of Products - Background and Guide"***, Centre of Environmental Science, University of Leiden (NL).

15. Clift, R. ***"LCA and Ecolabelling"***, (1993) **J. Cleaner Production**, 1 Nos. 3-4, pp. 155-159

16. Keoleian, G. A., and Menery, D., (1993) ***"Life Cycle Design Manual - Environmental***

*Requirements and the Product System"*, US Environmental Protection Agency EPA/600/R-92/226 (USA).

17. Yates, A. J. and Clift, R., to be published.

18. Giarini, O. and Stahel, W. H. (1989) *"The Limits to Certainty"*, Kluwer Academic publishers, Dordrecht (NL).

19. Jackson, T. D. (1995) *"Material Concerns"*, Routledge, London (UK).

20. Clift, R., (1993) *"Pollution and Waste Management"*, **Science in Parliament** 50, 29-32

21. Clift, R., (1995) *"The New Industrial Ecology"*, pp 129-143 in **Advanced Materials in the Market Place**, ed. J. E. Castle and M. J. Kelly, The Institute of Materials, London (UK).

22. Corbett, J. R. Wright, K. and Baillie, A. C., (1984) *"The Biochemical Mode of Action of Pesticides"*, Academic Press, London.