Environmental Protection: a shifting focus

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Abstract

The last two decades have seen a fundamental change in the way chemistry handles environmental issues. A shift in focus has occurred from ‘end-of-pipe’ to prevention and process integration. Presently an even more fundamental change is brought about by the need for sustainable development. It is becoming the incentive for much of the research and development in chemistry and engineering. Visions and approaches on the role of chemistry and the way chemistry is done, change. New knowledge is constantly needed. But the existing knowledge should not be discarded. It must be used in new ways. It asks for new thinking and novel methods for research and engineering. Chemical engineering education will have to take up this challenge too.

1. Introduction

Environmental protection is the responsibility of us all. In particular the chemical industry has learned over the last 40 years that neglecting this responsibility can be extremely costly. So chemical engineers must care. All fields of chemical engineering are involved. Any chemical activity involves environmental aspects, as a result of the compounds used or produced (often unintended), the ‘inevitable’ emissions, waste streams and of course the possibilities of spills due to leaks or incidents. At the same time in the treatment of environment pollution, prevention and abatement technologies are involved, as well as other fields of engineering sciences.

Environmental protection is therefore itself a field of engineering that connects various other fields, transverses boundaries and can add knowledge to all fields of engineering. As such it is has become a specialist engineering field itself. That poses the risk that it also becomes somewhat isolated field. That can and does sometimes lead to a situation where environmental protection is not integrated into chemical engineering and therefore not in the development and design of processes and plants. From that results what often dominate environmental technology: ‘end of pipe solutions’.

This should change. And indeed it is changing. The scale of environmental impacts grows and so grows the awareness that more fundamental approaches are needed. The knowledge needed for that is better defined. At the same time science and technology in these fields develop at a fast pace. So the need and solutions for such approaches are becoming increasingly visible.

2. A shifting focus

Environmental protection has come a long way in the last 40 years. In the sixties and seventies of the last century it started with grudging application of technologies to clean up pollution caused by operation of plants, use of products and discarding of wastes. That technology has evolved from simple equipment based on simple principles to often complex equipment using the latest knowledge in the various fields of engineering. Soon it became clear that prevention of pollution was much more effective and economically sound. That influenced the way the technology was used, from end of pipe

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to integrated solutions aiming at prevention. Chemical engineering as a whole has changed too. New technology and new optimization techniques have been developed.
Over the last 20 years awareness has grown that pollution as such is not the main issue but just one of the side effects of wasting the resources we need for a sound and sustainable economy. Chemical engineering has to change even further. The role of chemistry in the development of the economy and society as a whole will have to be assessed. New directions are asked for.

Thus, looking back and looking into the future shows a continuous shift in focus in the field of environmental protection and of chemical engineering as a whole. It concerns all aspects: the development of environmental technology, the way it is used, the priorities within chemical technology development and the role of chemical engineers, their views and their training.
This shifting focus has made the field of environmental protection one of the fastest changing fields of knowledge in the last decade. It is quite likely that this will continue to be so in the coming ones. It is a challenge for chemical engineers and for the chemical industry. This paper outlines the various shifts in focus and the subsequent development.

3. Not yet end of the line for the end of pipe

Environmental technology comprises a broad range of techniques, approaches and scientific fields. It treats pollution of gas-streams, water and soil. This involves mechanical, physical, chemical and biological methods. Often, certainly in the more advanced approaches, combinations of methods are used. So there is an enormous reservoir of options to treat all types of problems. Many of the technologies can be placed in other specific engineering areas from which the principles and basic knowledge can be drawn, for instance separation technology. Nevertheless they all share some common characteristics which make them different and justify a separate grouping as 'environmental technology'. One is of course their function: 'cleaning'. A more technological characteristic is that they have to work with material flows and under conditions which are mostly rather extreme, variable and not always well defined. Under these conditions they have to perform with high reliability, often reducing a already low concentration of compounds to even lower levels. This requires rather novel, and multidisciplinary approaches differing from the 'normal' engineering practice for production processes. Many successful technologies have resulted. Well known examples are anaerobic waste water treatment units that are compact and very efficient using immobilized micro-organisms (Nicolella *et al.,* 2000), and the widely used flue-gas desulphurisation plants producing commercial gypsum. On the other hand the high reliability required, does mean that promising technologies do not live up to expectations. A well known case is biofiltration that has not (yet?) achieved break through, although a novel approach, combining biofilters with membrane separation, might do the trick (Ergas *et al*., 1999).

Developments are of course continuing and the performance of the technology is improving. In particular energy consumption and use of other resources such as water and filtration material are being addressed. These issues determine to a large extent the costs of operation. Part of the improvement is attained by more sophisticated process control and automation of the equipment, so reducing operation costs and improving performance and reliability. However at the same time do the increasingly severe regulations, for instance for NOx and fine dust in air and heavy metals and POP (persistent organic pollutants) in water, lead to an increase in energy consumption and uses of other resources: better removal of pollutants tends to be proportional with energy consumption. Energy generation brings its own pollution and this requires much further attention therefore!
An important field of improvement is the requirement that pollution is not just relocated to another sector: air pollution becoming water pollution when scrubbing with water or waste turned into air

pollution when it is combusted. The first approach was to place abatement units after each other. This leads to a cleaning system that could be made of 5 or more different environmental technologies which is expensive and increasingly difficult to operate. Novel abatement techniques and concepts are needed.

There is a number of specific areas where the development of novel and improved technologies is necessary for some worrying environmental problems.

- Fine particulate (< 10 micron) in ambient air which causes a large number of deaths still also in the western world. A major source is formed by diesel engines.
- Volatile organic compounds, partly from processes, but also from diffuse sources as petrol stations, storage tanks and the use of products containing these.
- Persistent organic pollutants (POP's) which might be carcinogenic or disturb hormonal functions in animals living in the water, but might also end up in our food by various routes.

Technology areas that attract much attention for treating these and other pollutions include:

- supercritical wet air oxidation for efficient organic waste and waste water treatment that is also able to brake down persistent pollutants (Shaw et al., 2000);
- use of static electricity in filters for example to enhance removal of fine particulates;
- catalytic treatment for NOx and organic compounds both for 'point sources' and for more diffuse emissions by creating very large 'active surfaces' such as glass panes with TiO_2;
- extractive and biological treatment of soil pollution in order to achieve in situ remediation.

The major drive to develop environmental technology has always been laws and regulations. These were the result of a society that would no longer accept the nuisance and the potential risks involved. Such legislation seeks to correct problems that were often seen to be inevitably connected with processes and production. Furthermore it was, and often still is, the fastest method to solve such problems. Its costs are however high and it involves extra work and much attention in the operation of plants. It is a basically an illogical approach; create a problem and than solve it afterwards, 'end of pipe'.

So awareness has grown that prevention is better, cheaper, and often is perfectly possible. It takes more time to develop it but over the last twenty years the knowledge to do so has grown and in many instances 'simple' prevention has reduced pollution substantially.

Does this imply that such 'end of pipe' approaches and the technology developed for them will be phased out eventually? That does not seem likely for a number of reasons:

- Even with the much improved processes there will always be a remaining reject stream. Requirements and standards will become increasingly severe as a result of better insight in the risks involved and a critical society that demands better quality of life and does not accept the unpleasant side effects of industry.
- In several cases it is the only approach possible, for instance for household waste water treatment or in situations where incidental pollution occurs.

A major reason however will be the knowledge and expertise that is put into many of those technologies. As said previously they have to perform under difficult and critical conditions and so these technologies and approaches can also be integrated into the processes. They can be used to prevent emission and pollution, catching it at the source and redirecting compounds into the process. They can remove possible pollutants at an early stage in such a form that they are cheaper to dispose of or can even be a valuable product. This requires a new view of the potential of those technologies not only by the 'environmental engineering' specialist but also, perhaps even more so, by the generalist engineers developing processes and production plants. This is one of the particular intentions of the European Commission in its action plan for environmental technology (EC, 2004).

Figure 1 shows this shift in focus schematically. It also shows where the role of specialists must be taken over by the general engineer, of course still supported by the specialists.

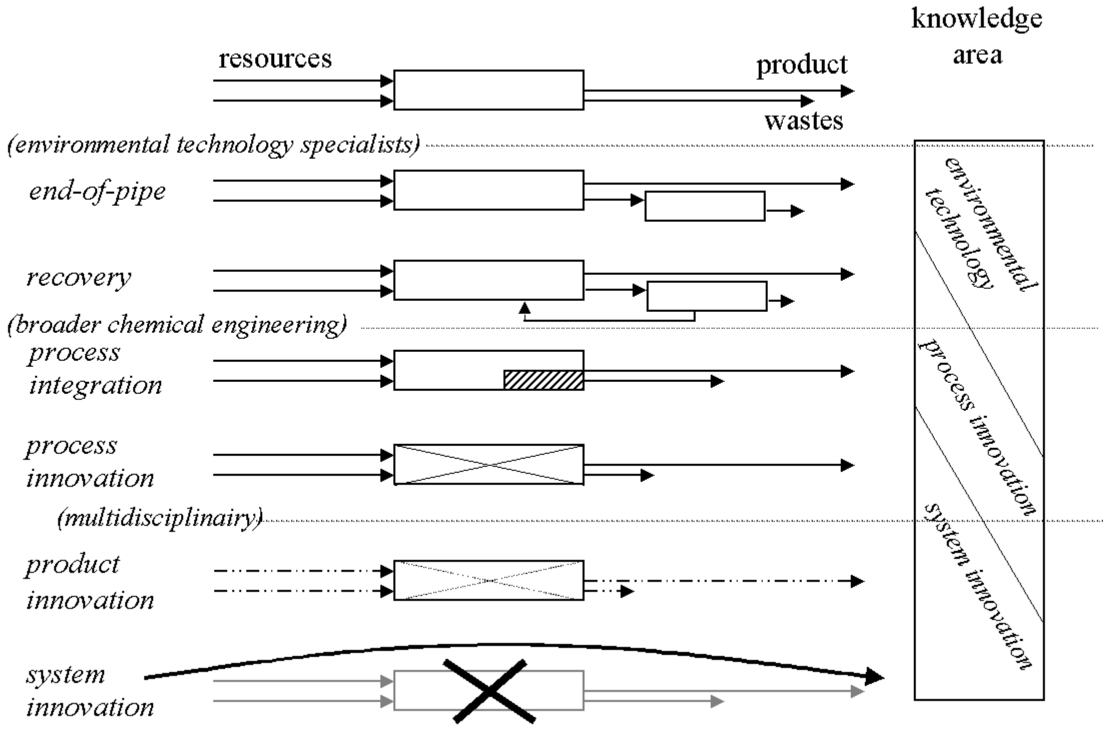

Figure 1 Development of environmental technology from end-of pipe to total integration

The phases of development involved go from 'pure' end-of-pipe technology to one in which valuable materials can be recovered. Eventually it leads to integration of the technology in a process, acting as a separate unit to remove and reclaim and eventually to new processes in which the 'environmental' technology is completely integrated in the process and reaction concept. An example is the use of membranes to remove compounds directly from a reactor.

The next phases shown involve a greater shift in focus. Here totally different process and routes are developed to produce the necessary products or services. This will be discussed below. Nevertheless, developing these new processes and plants requires the knowledge of many different fields. Although the specific knowledge present in the field of environmental engineering and technology will continue to be valuable.

4. Prevention by integration and optimization

The shift from 'end-of-pipe' to more prevention oriented approaches when developing and designing processes and installations, is based on activities in various areas:

- more efficient and cleaner reactions and processes;
- process intensification;
- process integration;
- recovery and reuse;
- life cycle assessment and chain management of processes and products.

It covers a broad area and crosses the borders of the 'normal' fields of chemical engineering. Many of the activities and developments are multidisciplinary. Knowledge of the environmental issues involved and environmental technologies is however essential to attain effective prevention to the level required (CEP 2000).

A major focus in all five areas is development of models, structured approaches, mathematical algorithms and software instruments. These make it possible to ‘rethink and redesign’ reactions, processes and the set up of production units, not just to optimize the existing processes but ultimately to develop totally novel approaches that lead to extremely efficient and clean production chains. Combining those into a coherent way of working is ‘process system integration’ (PSI), defined as a concept for network synthesis with the objective of optimising resource utilisation within a total product and materials chain.

One of the major challenges for PSI is the matching, and eventual coupling, of the modelling instruments and the assessment and optimization methods. One group of models and instruments deals with development of reactions and equipment, with design and installation and with process control when operating production plants. For optimizing environmental care and a good focus on prevention options these have to be combined with life cycle assessment and total production chain management. This combination would form the right ‘instrument’ to develop effective ‘sustainable chemical production’. Figure 2 shows the various tools and their optimal interaction.

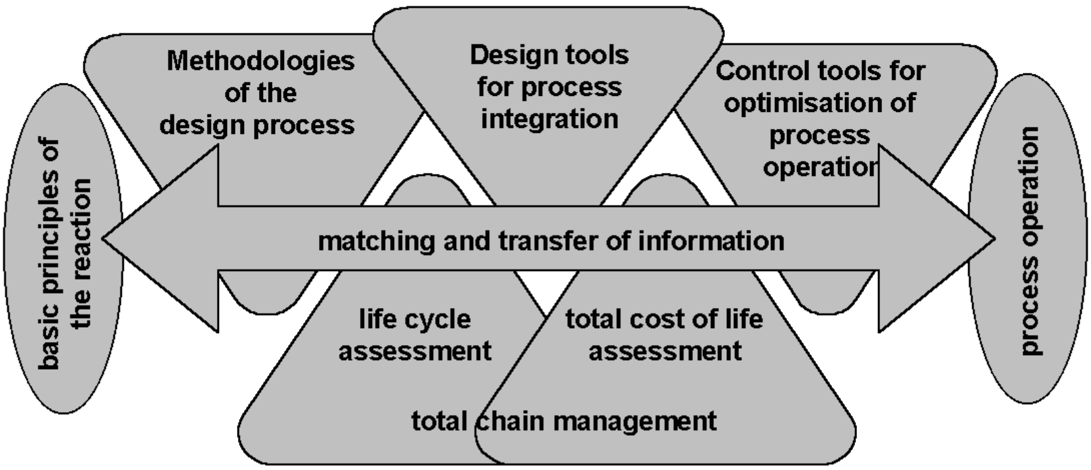

Figure 2 Tools for Process System Integration aimed at sustainable chemical production

The major focus of the first two areas for development mentioned above; ‘more efficient processes’ and ‘process intensification’, involve radically novel technology.
The concept ‘Green chemistry’[2] is often used for the development of cleaner processes and products. It aims at reactions which are much more selective and result in a higher conversion. It would result in a much reduced size of reaction systems needed for the same production volume and reduce the necessary recovery and recycle streams. The total system would be smaller and require less energy and lower use of resources on the whole. Further aims are the use of raw materials with less potential pollutants and changes in solvents. The potential risk some compounds, raw materials and products, pose when they enter the environment, or when people are exposed to them during production and when used in final products, is of growing concern. Strict regulation is being developed, such as Integrated Pollution Prevention and Control (IPPC) and REACH in the EU. This is becoming a major incentive for developments in this field. Tight process control is essential too. Reaction conditions

[2] The concept ‘green chemistry’, and others such as ‘industrial ecology’ described later, sometimes cause confusion. They are used also for the workfields of environmental care, process integration, sustainable chemistry and development etc. as a whole. Here they are used in a more strict interpretation.

need to be kept within increasingly strict and narrow conditions for high selectivity and to prevent incidents.

Process intensification in particular is aimed at downsizing the number of process units, by integration of different process functions in one piece of equipment (for example conversion and separation in a membrane-reactor). A change from batch wise to continuous production systems is often an option and novel types of reactors are being developed to achieve this change.

Catalysis is an essential part in both the developments mentioned above. The goal is the transformation of multi-step processes using separate catalysts in the sequence of reactions into single step processes applying more catalysts at the same time, as well the combination with enzymes with chemocatalysts. These resemble the biochemical activities that take place in a living cell, so-called ‘bio-mimicking’. Total process chains can be ‘shrunk’ to one or a few steps. The potential of the developments in this area is very large (Bruggink *et al.*, 2003).

The focus of the three other areas of activities is on optimizing, rethinking and redesigning through assessment and modelling. Process integration concerns optimisation of chemical processes and processing plants, aiming at minimising energy and feedstock consumption. Methods and tools here include pinch technology, exergy analysis and exergo-economic analysis. Presently pinch technology is evolving further into a tool that can handle the synthesis of an entire utility network in the chemical industry. Based on the pinch technology concept, the water-pinch is being developed, to reduce water usage. And attempts are being made to synthesize mass exchange networks with the purpose of minimising waste production. It has proved to be a very attractive concept as it reveals cost-effective measures for environmental performance improvement.

The concept ‘Industrial ecology’ is used for developments aimed at recovery and reuse of materials, water and energy that were considered unusable and thus ‘waste’, previously. This applies to wastes resulting directly from a production but also waste generated from discarded products. Recovery and reuse involve, again, a broad range of technologies. Some of those are conventional chemical technologies, others involve technologies which stem from developments within environmental technology as described before. A major issue is the development of a ‘concept’ to connect ‘wastes’ (materials but also water and energy) with ‘needs’ for a specific raw material. It might be necessary to change the process that generates the waste and the one that uses it as resource again. It is often not so much a technology issue as a change in vision, requiring changes in management, operation and logistics.

Life cycle and chain management create a total view on the environmental and resource consequences of product and materials chains, from resources, processes, product use and eventually discarding and recycling. These are used as evaluation tools for environmental impact and developments are taking place to make the concepts more widely applicable for ‘total chain management’. Other aspects such as maintenance, costs and control, then become integrated. As such these offer useful tools for a network synthesis approach. Life cycle analysis is well-known. It is used to assess environmental impact over the whole life span of products and processes. Instruments are being developed for total cost of ownership that amongst other factors take maintenance costs into account.

Still much has to be done, not only to combine the tools for ‘process system integration’ but also in the separate fields. A current development is the adaptation of process integration tools for systems incorporating more production units. For batch processes the tools also have to be adapted further. New concepts in chemical reaction engineering, such as process intensification, demand new and adapted tools while life cycle and total production chain management concepts must be developed much further, incorporating the new ideas of sustainable chemical development.

The various process optimisation and integration tools are as yet mainly used with the aim of better and more economical processes. Pollution prevention is often still ‘only’ an extra spin-off. Reductions of energy consumption, of resource use such as for water and raw materials, reduction in costs for abatement and for removal of wastes, offer a strong economic incentive. It was for these reasons that the ‘Pollution Prevention Pays’ slogan was used. However that suffices only to a certain level. When the presently existing global problems are considered it is clear that chemical technology must develop further. Another shift in focus is needed.

5. The challenge for chemical engineering

The focus and scope of environmental care has indeed widened further. From specific attention to short and long term impacts of pollution, it has evolved to a concern for prevention in combination with much more efficient use of resources. But present concerns go far beyond this. Growth of the economy puts much stress on resources and the environment. Yet, growth is necessary. The world-population is increasing and worldwide people wish for a legitimate share in prosperity making economic growth necessary. Allowing for the expected population growth (a factor 1,5 to 2 in 40 years), a justified claim for more prosperity globally (a factor 3 to 5) and the presently existing pollution, it is estimated that (eco-)efficiency overall has to increase by a factor 10 to 20, and even more than this to attain sutainable economic growth. Besides, such a substantial improvement in the ‘eco-efficiency’ of our activities cannot be based on changes in technology alone. Socio-economic and cultural changes will occur. So developments needed within chemical engineering will also have to keep those in its focus (von Weiszacker *et al.*, 1998; STD Vision, 1997; Weaver *et al.*, 2000).

It has become increasingly clear that the approaches described above are needed, but are not sufficient in the long run. The positive effect of better waste management, pollution abatement technologies and cleaner processes by prevention and integration will be off-set by the ongoing growth. ‘Decoupling of economic growth and resource use’ is essential. New approaches, radically innovative and integrated, are needed, and these will require totally new technologies and novel ways to apply technology. Figure 3 shows the successive approaches graphically which table 1 gives some of the essential characteristics.

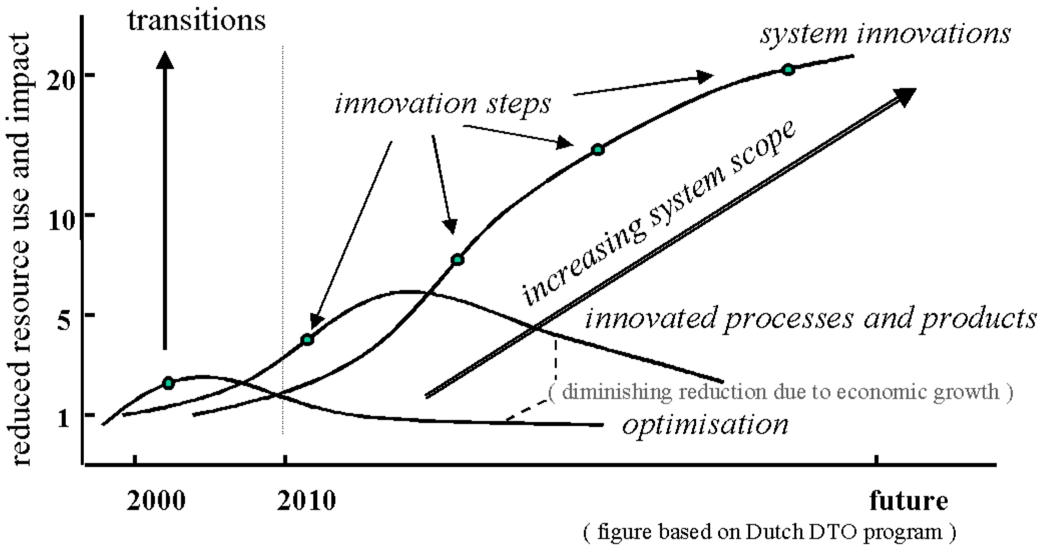

Figure 3 Three steps towards sustainability (STD Vision, 1997)

	optimisation	innovation	novel system approach
period (yrs)	3 – 5	5 – 15	10 – 40
characteristic	good-house-keeping improved operations	process / product innovation	novel business concepts, system and service oriented
improvement	tens of percent	factor 2 to 4	factor 8 to 20
(technical) options, examples	end-of-pipe process optimisation	low energy, solvent-free processes / products, low-waste	renewable resources and energy, captive use, novel processes, closed material chains
main field of attention	operations, permits, environmental management	development and design	management, business, marketing
main aspect	better organisation, implementation of existing technology	new concepts, process-integration	socio-economical requirements, quality of service delivered
economic effect	high costs	cost reduction and optimisation	new opportunities, improved profits

Table 1. Characteristics of the three approaches

The major challenges chemical engineers face therefore, are:

- ✓ define and develop the compounds, materials and products that address the challenges set at above, being highly effective for the intended use and applicable with minimal environmental impact and risk and easy to recycle;
- ✓ develop the materials and products required for low cost renewable energy sources for example high efficient (organic) solar cells, biomass based fuels, fuel cells etc.
- ✓ find and develop the processes and production paths with the necessary equipment that are extremely efficient, clean and safe, regarding new production paths completely beyond 'just optimisation' of existing ones. Reduction in size of installations is an added goal.
- ✓ develop paths to make shifts possible in the resources on which production is based, in particular towards renewables such as biomass based resources for raw materials and energy;
- ✓ closing material cycles for the major non-renewable resources by developing the necessary (extremely efficient) recycling paths, processes and necessary equipment at the one hand, and on the other hand by developing the production processes that can be based on those recycled resources;
- ✓ methods to design and test reactions, processes and products, to scale up reaction and production systems: for multiple screening, laboratory on a chip and simulation and process architecture design.

All chemical engineering fields will be involved, not least environmental technology, prevention, process integration and intensification as described above. The new factor, crucial for sustainable development, is that they are combined and optimally 'tuned' to attain a really substantial reduction in the use of resources. Coherent development is needed. The structure of such a coherent approach is shown in figure 4 which gives the outline of the chain which links resources, processes and products.

Only by using the improvement options of all steps in this chain in a coherent way can the earlier mentioned factor 10 to 20 in overall resource use efficiency be attainable. The major areas within chemistry and chemical engineering that play a role in such a system approach are indicated.

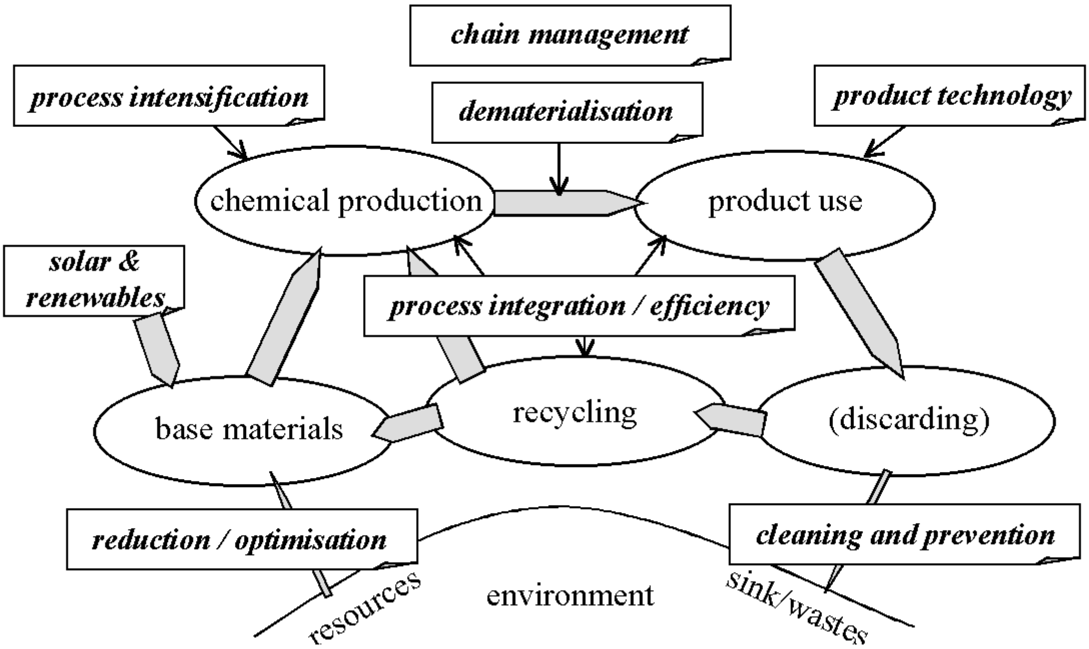

figure 4 Coherent approach of all fields for sustainable chemical engineering development>>

6. Focus on special fields of chemical engineering

For sustainable development much attention must be focussed on a number of specific fields.

Major issues for sustainability are dematerialisation and higher quality of products with better functionality. These will perform "better with less" and are able to create extra functionalities which also improve competitiveness. Optimised 'design' of compounds and materials for their specific function is a major field of research and development. Molecules are developed to give the precise intended effect and no other, as in pharmaceutical products for example, or leading to a much better materials performance when they are applied, optimisation of weight to strength ratio for example. Developing these new and improved products can (and maybe should) be the major driver for chemical engineering (Bruin, 2003). The knowledge required to link the micro and meso-levels by predicting the behaviour of molecules, groups of molecules and sub micron particles and so predicting the performance of the products and materials these are used in, grows. This area of development has been identified as one of the new frontiers for chemical engineerin (Villermaux, 1996)g. The possibility to create very specific molecules and clusters forms the essential basis of many other fields of engineering as in nanotechnology and microelectronics. A fascinating area, and one of enormous social importance, is the development of drugs and additives for so-called functional foods that are much more 'targeted' for a specific activity and even towards the specific personal characteristics of patients.

Biomass as a resource, and process routes based on biotechnology, are fields on which much attention will be focussed. Research aims at better use of organic materials from crops and wastes for example by biorefinery and biocascade approaches. The objective is to use the total mass of a crop, starting with the most valuable compounds but utilizing even the final residues in an economically sensible way (Venselaar *et al.*, 2001). Major obstacles for application of biomass in economically feasible ways, include the complexity and variability of biomass resources. In addition to this logistic questions that arise from the bulk of biomass, its perishability and the seasonal character must to be solved. Tuning and linking of agricultural and chemical industry operations are also needed. Nevertheless much effort is focussed on this area in many countries (USDOE &DOA, 2002). For fine chemicals and low volume specialty chemicals in particular it is considered to be an promising option

In the field of biotechnology genomics research is high on the agenda and has the potential for major breakthroughs. It focuses on the development of new bio-based conversion methods based on increased fundamental insights into the metabolism of living cells and the underlying genetic information. The main feedstocks will be carbohydrates and vegetable oils, which are widely available from normal crops but also from residues and wastes. New biotechnological routes are being developed to convert all types of cellulosic type raw materials, for example crop or wood wastes, to fermentable sugars. Combining molecular biotechnology with advanced bioprocess, 'normal' chemical technology and developments in process intensification makes biomass-based production of fine and bulk chemicals feasible. It can lead to a change from the 'classic oil based' production routes into process routes consisting of a few steps, or even a single step based on biomass. An example is the development of the commercial production of caprolactam and phenylalanine from sugars, a process that si much advanced. Many other are being investigated (ABB, 2002).

7. Education is an essential factor

A shift in focus also has to occur in engineering education, and this is already taking place.
Environmental technology has usually been treated as a specialization within engineering studies. Commonly it was an interfaculty or interdepartment activity because of its multidisciplinary character. Most technical universities offered environmental engineering studies. Nevertheless care of the environment as a specific subject remained rather isolated from the 'normal' engineering curriculum. The so-called 'greening of the curriculum' has been promoted but not with much success. It is generally confined to voluntary courses and to specialisations taken only by a few. As a result the traditionally educated chemical engineer has been insufficient aware of the background of environmental issues and the way to handle them. The 'end of pipe' approach to environmental care has therefore been prolonged quite unnecessary.

With the shift in industrial focus to pollution prevention, cleaner production, reduction of energy consumption and more efficient use of resources, this approach to education is changing. Industry is taking an interest in better education of future engineers in this respect too. Process integration and optimisation tools are now more familiar subjects to students. But many of the more specifically environmental assessment and optimizing tools are still only studied by those specifically interested in them. The 'greening of the curriculum' has also with respect to prevention still not progressed sufficiently.

Sustainable development is now making this relatively uncommitted approach impossible. Engineering studies will have to show how the 10-20 fold reduction in resource can be attained. This requires not just attention to process development and design of installations as such. The system approach that is essential to attain such objectives makes it necessary for students also to become familiar with the needs and consequences of sustainable development. Methods to determine how resources, technology, materials and products are to be developed and used in the most optimal way and to assess which are the most acceptable and comfortable solutions, in the long run, must be learned by all. That is a daunting task. Nevertheless universities in many countries have taken up this challenge and chemical engineering studies are often leading the field (Guttie-Martin *et al.*,2003; Venselaar *et al.*, 2001; Lemkowitz *et al.*, 2000; Azapagic *et al.*, 2000).

8. A prominent role for chemistry

A sustainable future requires products and materials that have a high functionality and offer minimal risks. This demands new molecules and ways for their production and use. The envisaged growth of new technologies such as nanotechnology, microelectronics and pharmaceutics is based also on new molecules and better handling of molecules. So, (new) molecules will shape the future, but only with an active role of chemistry and chemical engineering.

Furthermore economic growth needed for better living conditions worldwide, is unattainable without the products of chemistry.

Combining sustainable development and economic growth is therefore the current challenge and frontier for chemistry and chemical engineering. It identifies the future direction for chemistry to take. And it might also improve the image of chemistry and reverse the dwindling numbers of students to the discipline.

In retrospect past ages are sometimes characterized by a field in which much development has taken place and so shaped society. Thus the 19th century: the age of mechanisation; the 20th century: the age of electricity and electronics. Could it be that in view of the need for sustainable growth and radical reduction in use of resources, the 21st century should become ‘the age of chemistry’?

Acknownledgement

This paper reflects the activities of the EFCE Working Party on Environmental Protection over the last 10 years and the shift in focus that occurred also in its views and activities. As a consequence recently ‘and Sustainable Development’ was added to its name. Venselaar has been a member since 1991 and chairman from 1999 till 2003. He wrote and presented a series of papers on the subjects covering that shift in particular the how to integrate sustainable development (Venselaar 1999; Venselaar 2001). The author acknowledges all the contributions and the close cooperation by his fellow working party members in the activities of the working party. Together they made it possible to chart that shift of focus in our field and to convey that to the EFCE as a whole.

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