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Sustainable Processes – The Challenge of the 21st Century for Chemical Engineering

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Abstract

The 21st century inherits stark challenges for human society: environmental degradation, global warming and shrinking fossil resources. All these problems are paired with a dramatic growth of the economy in China and India, home to 2.3 billion people. We need to make more from less and we need to do this while reducing our impact on nature by the order of magnitudes.

This challenge is particularly tough for chemical engineering. This sector is on the one hand responsible for providing most of the products of daily consumption, the base for modern agriculture as well as energy carriers for power generation, transport, heating and cooling. On the other hand chemical engineering has a considerable impact on the environment, via its resource consumption, its emissions and the impact of its products.

Chemical engineering will have to explore new ways in order to stay ahead of these challenges. The paper discusses some of the aspects of the changes that process engineering will face in the 21st century as it will widen its raw material base to include more renewable resources and simultaneously reduce its environmental impact. As a result, the structure of process industry will be transformed dramatically. Existing design principles and methods will also be challenged and adapted to the new challenges of sustainable development.

Given the strong impact that the challenge of sustainable development will pose to process technology engineering education will have to change accordingly. For the first time in decades, process engineers will again be faced with developing new processes rather than process optimisation. They will need to understand how to integrate processes into the ecosphere, how to set up raw material logistics and will have to deal with stake holders outside industry. The process concept will become more encompassing and include the life cycle of products. All these new skills must be taught to students today to make them fit for their carrier in the 21st century.

Keywords: sustainable processes, renewable resources, process synthesis, process evaluation

1. Introduction

Chemical engineering has from its beginnings been shaped by characteristics that have a distinctly "modern" ring to us we turn into a new and challenging century. Among them are:

- a strong interdisciplinary streak, as chemical engineering bridged gaps between chemistry, physics and mechanical engineering;
- a strong penchant for systemic thinking, as evidenced by the systemic approach to chemical processes in the "founding charter" of chemical engineering, the book "The principles of Chemical Engineering" by (Walker, Lewis and McAdams, 1923) that gave rise to the fundamental concept of unit operations;
- a distinctly problem oriented approach that utilises the contributions from many disciplines, experiments as well as modelling and innovation to solve pressing problems of society like energy provision, environmental protection and increasingly also the provision of high tech materials and pharmaceuticals.

These characteristics have helped chemical engineering to branch out into a number of other fields, like food industry, the pharmaceutical sector and environmental engineering. They have also been responsible for the strong presence of chemical engineers in the general discourse about sustainable development.

Today these characteristics will serve the chemical engineering profession well as it faces a profound change in the framework in which it operates. Three challenges will be especially formidable and will shape chemical engineering in this century. They are:

- **The change of the raw material base**

Today chemical industry is mainly dependent on fossil oil and gas as its main raw material base. Both resources will face their production peak during this century, forcing process industry to look for alternative resources.

- **Life cycle stewardship**

The pressing problems of environmental degradation, especially global warming, require new approaches towards providing services to society. There are two overriding principles for chemical industry in the 21st century: highest possible efficiency and lowest possible environmental impact. Both can only be fulfilled if the sector will take over the responsibility for his products from the generation of raw materials to the re-integration of residues and wastes. Thus chemical engineering will become concerned not only with constructing processes but with developing and optimising whole life cycles of products.

- **New construction principles**

For the first time since many decades process industry will have to generate new industrial structures for whole value chains. Besides economic optimisation the reduction of the ecological impact over the whole life cycle will become a necessity.

This means for chemical engineering to apply new principles for the construction of its processes: process synthesis and ecological process evaluation will become prominent tools for the chemical engineer in the 21st century.
In the following chapters, these challenges and some approaches to meet them will be discussed.

2. A Sustainable Raw Material Base

Since WW II crude oil has become the main resource base for chemical industry. It is interesting to note at this point that the "love story" between crude oil and chemical industry is relatively short: in fact the chemical sector followed the general raw material source of society from agricultural resources to coal to crude oil.
Most studies about the availability of crude oil (e.g. Schindler & Zittel , 2000) point out, that we will experience a peak in production of this resource some when in the first quarter of the 21st century. The way up to this "peak oil" will be accelerated by the growing demand in countries like China and India with their double digit economic growth and their tremendous markets.
It is important to note that "peak oil" does not mean that crude oil will no longer be available: quite contrary, peak oil will designate a point of maximum production of this resource. However it will also designate a time when production cannot anymore follow the ever increasing demand of a global society. The consequences of this situation are evident: increasingly volatile markets and an upward tendency in the prices of this basic commodity.
For the chemical sector this requires a re-orientation of his raw material base. A change to natural gas seems to be shortsighted, as the same sources predicting "peak oil" also predict a "peak gas", just another 20 to 30 years down the line. A fall back to coal will require high costs in the face of global warming fears, as coal makes an over proportional contribution to CO_2 accumulation in the atmosphere and abatement technologies like CO_2 capturing and sequestering are expensive and probably unpractical for the chemical sector.
Obvious candidates for a sustainable resource base for chemical industry are therefore renewable, biogenic resources. Such a change in the raw material base however entails a profound revolution in the structure of processes, the technologies employed and the economical framework of process industry. Some important problems must therefore be solved if this shift in the raw material base should become reality.

2.1. Competition for limited resources

For one, these resources constitute a "limited infinity": although they may be provided for infinite time, their productivity is limited. The chemical sector here enters competition not only with the energy sector (who also sees renewables as alternative resources) but with the food sector, too (see table 1).
As can be seen from this table, future pressures on renewable resources may become severe. Even if a decrease of the energy spent per € of GDP of 50 % is factored in the increase in energy demand will be dramatic, from about 7 Giga tons carbon per year in fossil fuel to up to 37 Gt C/a on the base of biomass or coal. If the world population also grows to approximately 10 billion people agricultural production will have to

increase accordingly, to at least 9 Gt C/a. If taken together, this will bring annual consumption of carbon perilously close to the annual biomass production of 60 Gt C/a. Such a scenario will thus call for almost total appropriation of natural carbon production by man and may therefore be infeasible.

Table 1: Current and future (2050) consumption factors for carbon based resources in Giga tons carbon per year, following (Siirola, 2007)

Consumption/production factor	**Gt C/a**
Current fossil consumption	7
Current chemical production	0,3
Current cultivated crop production	6
Future resource requirement (from coal or biomass)	37
of that	
Future energy demand for transportation	12
Future chemical demand	1,5
Future crop demand	9
Annual terrestrial biomass production	**60**

Table 1 clearly points towards a critical raw material competition that the global society and industry in particular will face over the next decades. Biogenic resources will certainly become important players in energy as well as chemical industries. They are however no “drop in” alternative that will consistently and completely replace fossil raw materials. The chemical sector, though playing a more visible role in future, will still remain sort of a junior partner to the other competitors, namely the food and the energy sector. It will provide high tech materials for other industries and most of the energy carriers for transport. Chemical industry however needs a material resource base (contrary to the energy sector, who can also deal with direct solar radiation) and will therefore have to enter this competition.

Three important consequences for chemical engineering arise from this new competitive renewable raw material base:

- **Utilising technology flexibility to avoid competition**

It is obvious that some competitors, namely the food sector and also the pulp and paper and construction sector have very strict requirements for their raw material base. Whereas the former is restricted to the utilisation of edible parts of plants and animals, the latter are restricted to forest products of a certain quality for most of their products. The energy sector is less restricted by raw material quality than by logistical and economical requirements.

From all these competitors the chemical sector is the most flexible in utilising raw materials. Chemical engineering has in the past already shown its prowess in transforming unwieldy raw materials into valuable products. It may therefore turn to materials that may either not be used by other competitors or that are “by products” or even wastes of the utilisation of biogenic resources of other industries. A sampling of these “new raw materials” that may well form the bulk of chemical industry raw material base in 2050 is shown in table 2.

As a mater of fact, the switch to biogenic raw materials can even make chemical engineering more profitable. Unlike fossil raw materials biogenic resources show a high degree of structure. Chemical engineering may therefore in future not only look at efficient ways to synthesise products from small molecules but also increasingly for ways to utilise the "natural synthesis power" of plants and other biogenic resources. The more other sectors mobilise renewable raw materials the more chemical engineering will have to look into ways to utilise all the high molecular building blocks in their by products and wastes, such as fibres, complex organic molecules and natural polymers, to name just a few.

Table 2: Examples for "new biogenic raw materials" for the chemical sector in future

Raw material category	Material
Underutilised crops/resources	
	Gras
	Algae
	Sugar beets
Residues from agriculture/forestry	
	Low quality forest residues
	Straw from corn, cereals, oil seeds, …
	Corn cobs
	Leafs from beets, potatoes, …
	Cuttings from wine yards, orchards, …
Residues from industries	
	Tallow
	Slaughterhouse residues
	Oil seed cake
	Dried distillers grain
	pomace
	Tanning residues
Residues from society	
	Organic municipal waste
	Garden cuttings
	Used vegetable oil

Table 2 points towards the large variety of raw materials available for utilisation in chemical industry. All these raw materials (and many more, depending on the specific regional agricultural system as well as industrial structure in question) have in common that they have either a well established and cheap harvesting method or that they are harvested or produced in any case but are currently not or not sufficiently utilised. Taking these resources into consideration the chemical sector may well profit from a general increase of the importance of biogenic resources and avoid competition with other sectors for limited resources.

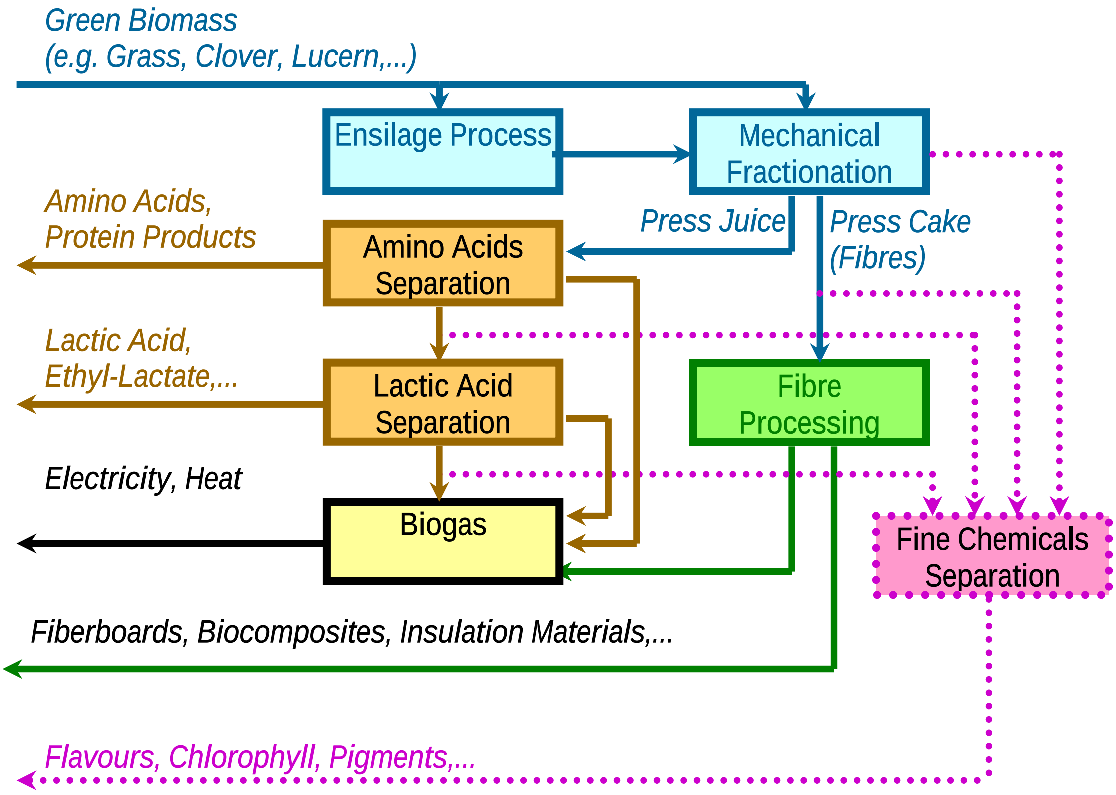
- **Utilising resources fully**

In all cases where competition increases, efficiency of utilisation is a key to success. The same holds true for the switch towards biogenic raw materials for chemical industry: as the raw materials become scarcer, engineering will have to squeeze out more products from less resource.

One important strategy to achieve this goal of utilising every raw material to its utmost potential is to create "cascades of utilisation". This means that a given raw material will be treated in a way that generates different products on different levels of complexity until the whole raw material is transformed in sellable products or energy services.

A good example for this strategy is the concept of the "Green Biorefinery" (Kromus et al., 2002). This concept (see fig.1) utilises green biomass like grass or leafy residues from crop plants such as beets to produce a spectrum of different chemicals, fibres and energy.

Fig. 1 Flow sheet of a "Green Biorefinery" (Mandl et al., 2006)



This approach however is neither new nor alien to chemical engineering. Any crude oil refinery utilises its raw material completely. The real challenge will be to find the product spectra with the highest overall added value for every raw material and the process networks that generate them.

- **Reducing energy demand and adapting to solar energy provision**

As fossil resources become expensive, global warming becomes a serious consideration and biogenic resources become increasingly sought after the chemical sector has to adapt his energy demand accordingly. By and large chemical industry has been at the forefront of increasing energy efficiency in its processes. Nevertheless energy saving will remain an important agenda for chemical engineering in the future. Almost all integrated utilisation concepts for renewable resources have one or more by products that may be used to provide energy. Chemical processes will increasingly become intertwined with energy provision, as the example of the Green Biorefinery shows. The challenge here will be to find the right pathways to utilise the energy provided by these processes. One possible bottleneck here is the combined provision of heat and power wherever a by product is thermally utilised. Power demand will definitely increase at a higher rate than demand for heat. This means that one of the major challenges for chemical engineers in the future will be to find interesting and rewarding ways to sell heat that may be generated by their processes.

In many cases though chemical processes will still demand more energy than they generate. Cheap energy in future will be linked to direct utilisation of solar energy. This will require either energy storage or adapting processes to the time dependent provision of thermal or photovoltaic energy (Müller, 2004).

2.2. Logistical optimisation of processes

Fossil resources are typical “point” resources, meaning that they are extracted in a small geographical area (the coal mine, the oil or gas field) far from areas of consumption and then transported to refineries and finally the consumers. Contrary to that, biogenic resources (as well as almost all other renewable resources based on solar radiation) are typical “dispersed” resources, meaning that they are provided by large swathes of land with a relatively low productivity per area unit. This means that they have to be collected, possible refined and then transported to production sites. From these sites the resulting products will be transported to retailers and consumers.

In the case of fossil resources logistics are much the same for any point on earth, meaning that logistics do not play any formative role for the process industry. This is however very different in the case of biogenic raw materials: not only differ the raw materials depending on regional natural endowments; their transport requirements are also complex and divers.

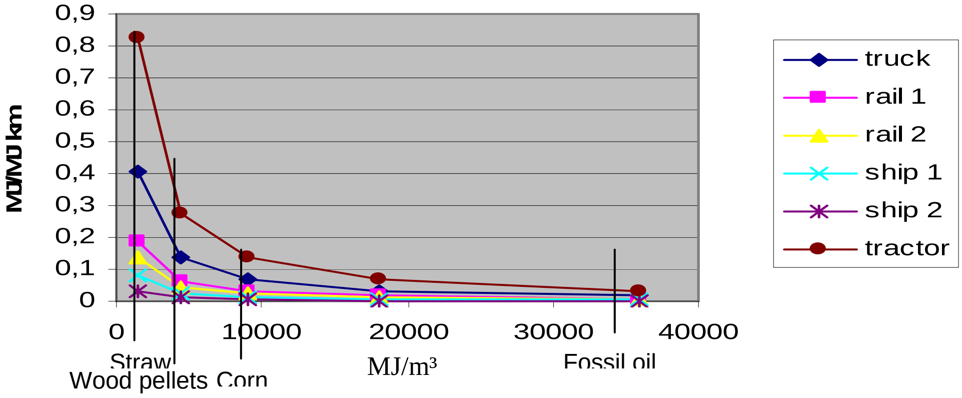
One major problem of many biogenic resources is their relatively low transport density, paired with relatively high moisture content. Table 3 summarises the densities, the calorific value (as a measure of the useful content) and the moisture content of some biogenic raw materials compared to light fuel oil. It is evident from this table that with biogenic resources transport becomes a major issue: transport vehicles use less of their capacity (as the densities are low) and a considerable part of the load is water that is of no use in the process.

The low transport densities indicate that the usual measure of “ton-kilometer” is no longer applicable as the limiting factor for transportation is no longer weight but space. An illustrative picture of the problem is shown in fig 2, where the energy to transport one MWh (as a measure of the useful content of a certain raw material) is shown.

Table 3: Logistical parameters for different biogenic raw materials

Material	Humidity [%w/w]	Calorific value [kWh/kg]	Density [kg/m^3]
Straw (grey)	15	4,17	100-135
Wheat	15	4,17	670-750
Rape seed	9	6,83	700
Wood chips	40	2,89	235
Split logs (beech)	20	4,08	400-450
Wood pellets	6	4,90	660
Light fuel oil	*0*	*11,86*	*840*

Fig. 2: Energy to transport 1MWh energy content of biogenic raw materials 1 km



This figure shows two important facts: transport with ships (ship 1 denotes river ship, ship 2 stands for ocean going ships) still gives insignificant energy demands for transportation when medium dense renewable resources like corn are transported. The transport of low density raw materials like straw or even wood pellets with tractors (e.g. from the farm to a processing site) or trucks however uses large amounts of energy. In order to highlight this even more one may suppose an efficiency to convert biogenic raw materials to transport fuel of 30 %. In this case a tractor would use up all energy it has in its load by travelling approximately 300 km. If the processing plant is 60 km from the farm, this means that the transport already uses up 20 % of the content of the raw material!

With this in mind it becomes clear that transport logistics become a shaping factor for process structures in the future. This is all the more evident when considering that there is not only the necessity to collect the raw materials but also to redistribute possible residues like biogas manure or ashes from combustions back to the fields in order to maintain the fertility of agricultural land. Again this usually means transport of low density goods and/or goods with high water content.

All this boils down to new process network architecture for utilising biogenic raw materials:

1. harvest and separate industrially interesting residues (corn, straw, corncobs, leafes, …)
2. pre-process, compact (and possible store) raw materials close to the farms in order to obtain transportable intermediates; use possible energy surplus (e.g. from biogas plants) locally or provide to transport grids (gas, electricity); return valuable substances as fertilisers to the fields
3. transport intermediates to central processing units where divers and valuable products are obtained that will then enter global markets; utilise possible energy surplus for other industrial processes or provide to transport grids (gas, electricity).

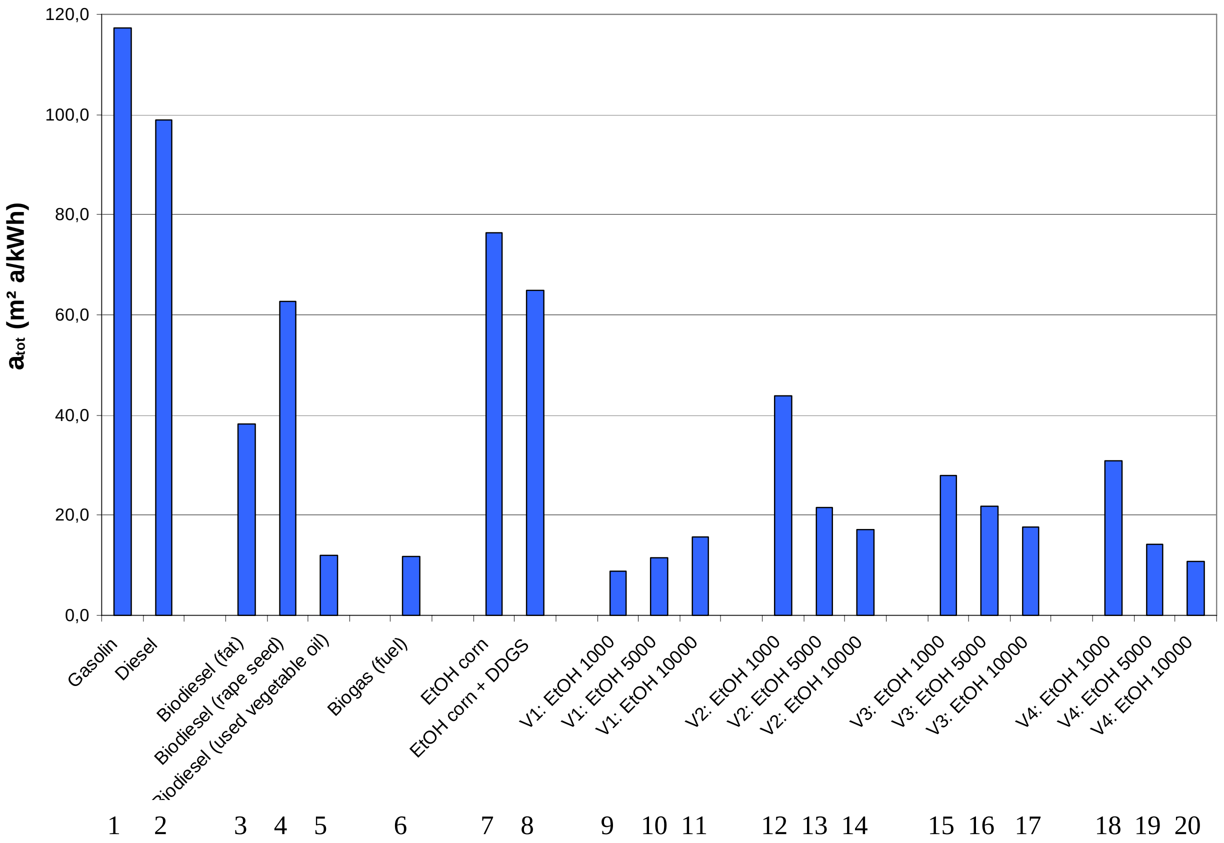
3. Life Cycle Responsibility

The ever louder call for environmental sustainability has a special meaning for chemical engineering: it is a key factor in the interaction between man and nature. The responsibility of chemical engineering will only increase as the raw material base is switching towards a larger role for biogenic resources. Through this switch the chemical industry in no longer just responsible for the environmental impact of its conversion processes. It becomes a main actor in utilising the natural income, namely biogenic resources created by solar radiation via the fertility of land and viability of oceans. This new role burdens chemical engineering with at least a partial responsibility to maintain fertility and viability of agricultural and natural systems.

In practical terms this new responsibility requires from the chemical engineer to keep the quality of the environmental compartments soil, water and atmosphere intact and to provide for recycling of nutrients to the grasslands, fields, forests and aquatic systems which yield the resources utilised in chemical processes. This requirement will profoundly influence the choice of technologies, the structure of the process network transforming raw materials to products and even the choice of the right size of chemical factories.

One of the major misunderstandings in this respect is that all processes that use biogenic sources are automatically “green” and sustainable. An illustrative example for the pitfalls of applying old design approaches to a new framework is shown in fig. 3. This figure shows the ecological footprint for the provision of various fuels calculated with the Sustainable Process Index (Narodoslawsky & Krotscheck, 1995; Krotscheck & Narodoslawsky, 1996). It compares on a well-to-wheel base conventional fuels like gasoline and diesel with bio-ethanol production in different plant sizes as well as with different technologies and biodiesel production on the base of different raw materials.

Fig. 3 Ecological footprint for different fuels (all bio-ethanol production alternatives on corn base)



This figure shows that fossil fuels exert the largest pressure on the environment (the two left bars in fig. 3). The differences in fuels based on biogenic raw materials however differ widely.

Bars 3 to 5 from left show the influence of different raw materials: bar 3 stands for biodiesel from fat (tallow) which is a by product of the rendering process of slaughterhouse waste; bar 4 stands for biodiesel from rape seed grown conventionally and bar 5 measures the ecological impact of biodiesel from used vegetable oil collected from households and restaurants. It is obvious that the by-product based biodiesel has a lower ecological impact than the one based on conventional agriculture. In the latter case, high pesticide and fertiliser requirements for the crop drive up the ecological footprint.

The lowest ecological footprint is achieved with biodiesel from used vegetable oil, a typical biogenic waste from society. In this case the ecological pressure for generating the oil has already been allocated to the primary use as food; the only impact for the raw material provision is here the collection of the used oil. One can very easily see that the new process network architecture derived in the previous chapter makes also sense from the ecological view point.

Bar 6 shows the ecological footprint for biogas as a fuel. In this case the low input to generate grass (which is the base for biogas in this case) is reflected in a very low ecological pressure for the whole fuel system.

The other bars depict ecological pressures for bio-ethanol production. Bars 7 & 8 measure the impact of conventional, medium scale plants (60.000t/a ethanol production). The difference in this case is that bar 8 factors in the sale of DDGS (dried distillers grain with solubles) as a product, which consequently bears a part of the ecological pressure according to the revenue obtained by selling it. The market for this product however will become increasingly narrow as bio-ethanol capacities grow all over the world. In general, it can be seen that by switching to biogenic resources without changing the process structure a moderate reduction in the ecological impact of fuel systems can be achieved (approximately 30%). This reduction is however far from the necessary dramatic reduction called for in the future.

Inspection of the other bars reveals some interesting insight to where the future of chemical industry may lay. They are grouped into different technological alternatives at different scales, from 1.000 to 5.000 to 10.000 t/a ethanol production. Bars 9-11 show the impact of an ethanol pant, where all residues from the raw material (corn) and the necessary crop rotation are feed into a biogas unit that provides process heat as well as electricity that may be sold. Bars 12-14 stand for an alternative, where a biogas unit is fed by DDGS to provide process heat for the ethanol production. Bars 15-17 show the ecological impact of a process where straw from corn is utilised as a heat source for the bio-ethanol production and bars 18-20 show the footprint of a plant that again uses DDGS in a biogas unit that also produces electricity with the surplus energy.

All these bars from 9-20 show processes that supply their own energy from locally provided biogenic sources (with the exception of bar 12, where the chosen source does not supply enough energy). What can be seen clearly is the dramatic difference between small scale plants entirely based on renewable resources and processes (bars 7 & 8) that use biogenic raw materials however supply their process energy still by conventional fossil sources (in our case natural gas). It must be stated here that the provision of biogenic energy carriers from the residues of harvesting the main crop is impossible above a certain scale of the plant as the transport intensity would become unbearable.

Within the “sustainable alternatives” we still can discern some interesting differences. Note that for bars 9-11 the trend concerning the ecological footprint as a function of the scale of the process is reversed to the rest of the cases. This alternative (biogas unit that utilises all biogenic material available) actually shows the least ecological footprint, due to the fact that it produces a large amount of electricity and that therefore the ecological impact is shared by different products. In this case transport has a strong influence on the footprint, especially as the biogas manure has to be transported back to the fields. This means that the larger the plant, the longer the transport and hence the higher the ecological impact. This technology is clearly interesting, however only in very small scale.

For the other alternatives transport plays a decidedly smaller role, as smaller amounts of residues have to be transported back to the fields. This clearly means that the larger the plant, the higher the efficiency in converting the resources to products and hence the lower the ecological impact.

Life cycle responsibility therefore poses completely new questions to the chemical engineer. Besides reducing the ecological impact of the processes themselves, the chemical engineer has also to consider the logistics of obtaining the raw materials and to ship residues back to fields and forests in the right quality and quantity. On top of that the chemical engineer has to observe the economy of scale and balance it against the “ecology of scale” that may in many cases run counter to the former.

4. New Methods for New Challenges

New challenges require new tools to tackle them. Two tools will come increasingly in demand if one follows the argument of this paper that major challenges for chemical engineering in the 21st century will be the change in the resource base and a much larger and formative role for considerations of sustainable development: process synthesis and ecological process evaluation.

Without going into detail on these two tools on which a large body of literature already exists, we will only highlight some requirements that these tools will have to satisfy to help bring about sustainable processes.

4.1. Process synthesis for integrated production networks

Process synthesis has along history in chemical engineering and is currently mostly employed for process integration, process intensification and optimization tasks. If however renewable resources become a major raw material base for chemical industry we will face a wholly different task: designing new plants with new and possibly untested technologies.

If we look at the requirements for process synthesis under these considerations we can see the following aspects:

- **Rendering results with fuzzy technology data**

There is a clear time pressure to come up with viable solutions for the utilization of renewable resources as the environmental concerns become more serious and the prices for fossil resources skyrocket. Although there are many technology ideas in the research pipeline, there is a distinct problem in finding viable production networks: single processes alone will not be competitive with (still cheap and well optimized) fossil competitors and production networks that may successfully spread the costs for (expensive) renewable resources over more products require complex and possibly spatially dispersed process architectures. In order to offer support in this situation process synthesis tools must generate optimized process structures on the base of data that are still based on laboratory scale research and simulation.

- **Integrating transport and plant sizing**

Transport will become a major factor shaping the architecture of process networks on the base of renewable resources. This requires that process synthesis tools will have to integrate transport aspects into the optimization of process structures.

An important problem in this respect is to find the right size and the right geographical distribution of different parts of the process network. The 21st century will see dispersed interlinked process networks, the time of the chemical plant as we have known it will possible come to an end. Process synthesis must give the answers to the construction of these networks, based on technology insight, the insight into the agrarian system and the logistical framework in a certain region.

- **Integrating time dependencies and scheduling problems**

Another important problem linked to renewable resource utilization will be the time dependent availability of certain raw materials. This means that process synthesis will not only have to deal with spatially dispersed process networks but will also deal with scheduling problems of adapting process chains to varying raw material supplies over a year.

(Halasz et al., 2005) have dealt with these requirements to process synthesis tools. This paper shows what strong support process synthesis can deliver to the tasks of chemical engineering. It shows however also how much still has to be done in this field.

4.2. Engineering compatible ecological process evaluation

Life cycle assessment has become a versatile tool to report the ecological aspects of production in many fields. The future task of chemical engineers, however, is to construct process networks from scrap that are sustainable. There is a marked difference between tools that are used for reporting purposes compared to those that an engineer may use to construct and optimize a chemical process. The following aspects may help to guide the development of "engineering compatible" tools that are still scarce:

- **Impact aggregation**

Chemical processes have divers impacts on the environment, however, engineers need to balance these impacts against each other in order to optimize processes: in the ever increasing number of cases engineers have already created highly efficient processes so that a reduction of one pressure usually leads to an increase in another. This means that engineers need tools that aggregate different impacts in a logical and scientifically sound way in order to discern between ecologically better and worse alternatives.

- **Flow sharp resolution of environmental pressures**

Chemical engineers deal with material and energy balances as their main tool in conceiving and optimising processes. It is therefore necessary for engineers to have tools at hand that measure the impact of each and every flow the process exchanges with the environment. This information is essential to discover "ecological hotspots", meaning raw materials, products, emissions or wastes that exert a disproportionate ecological pressure. Only through this knowledge can the engineer focus on fixing the real problems and avoid dealing with second rate impacts.

An interesting overview for the possible application of different highly aggregated environmental evaluation measures to engineering is given by (Krotscheck, 1997).

5. Conclusion

The 21st century will pose new and formidable challenges to chemical engineering: a change in the raw material base, increasing environmental considerations and the necessity to apply new methodological approaches. This century will however also bring new and increased importance to chemical engineering. It will penetrate into still more industries like the electronic industry, the pharmaceutical industry and biotechnology. It will also increase its importance for other industrial sectors, namely agriculture and food production.

In the light of these challenges and these chances we must adapt. Chemical engineering has long been a thoroughly technical discipline with a strong interdisciplinary streak. This base will help us to integrate even more systemic methodology and to acquire the necessary social skills to deal with new partners from agriculture to logistics to environmental sciences and regional development.

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