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Structural Prospects and Challenges for Bio Commodity Processes

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Summary

The current discussion about dwindling reserves of crude oil, rising fuel prices, global warming and supply disruption of natural gas has renewed interest in the provision of bioenergy and bio-based commodity products. There is a growing consensus that the 21st century will see a profound change in the resource base for industry and society, with less emphasis on fossil coal, oil and gas and more emphasis on renewable resources. This new resource base may take the form either of direct solar energy like photovoltaics and thermal solar energy or indirect utilisation of solar energy *via* biomass.

Such a change in the raw material base, however, entails a profound revolution in the structure of processes, technologies employed and the economical framework of industry and society. Renewable resources constitute 'limited infinity': although they may be provided for infinite time, their yield is limited. This paper explores the strategic challenges for society in general and process industry in particular, and indicates some methodological approaches to meet these challenges, exemplified in case studies about decentralised bioethanol production and decentralised multifunctional production centres.

The paper shows that utilising renewable resources enlarges the process concept by including resource provision and logistics into the process design. It also highlights a new balance between economy and ecology of scale when resource provision and logistics are taken into account. Ecological process evaluation as analytical methods and process synthesis as design methods will gain increasing importance for process technology as the share of renewable resources is increased.

Key words: renewable resources, process synthesis, sustainable process index, ecology of scale

Introduction

The change in the resource base of industry and society requires reorienting technologies as well as structures of industrial processes. Although there is a widespread consensus that in the long run human society will have to rely on solar radiation as the most important source for providing energy (and *via* biomass material) for its sustainable development, there is no single form of solar energy that will supplant current fossil resources. Siirola (*1*) clearly points out that biomass is not a viable general alternative to fossil resources as chemical industry, the energy sector and the food sector enter into a competition for bioresources. This fact was already driven home by recent turmoil about rising food prices that were attributed to an increase in the production of biofuels in particular. Wenzel (*2*) shows that the very fact of limited availability of biomass requires careful selection of utilisation pathways in order to exploit bioresources to their full potential in terms of reducing environmental pressures incurred by provision of goods

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and services to human society. From this vantage point, he favours direct use of bioresources for heat and electricity production over the use as feedstock for liquid fuel, regardless of the technology employed. As most other authors, he predicts a gradual phasing out of fossil resources during the 21st century, with biomass taking over the role as a resource for process industry and partly supplying heat for residential use, whereas transport will mainly rely on electricity from direct solar energy and combined heat and power (CHP) plants.

Another important aspect of the change in the resource base of society from fossil to renewable sources is the continued availability of fossil resources during much of the 21st century. The International Energy Agency (*3*) estimates that approximately double the amount of crude oil already consumed is still available at production prices below 30 US$. Almost 5 times the amount consumed so far will be available at prices lower than 70 US$ from various sources. This ensures that renewable resources face a stiff competition for the foreseeable future as the society is slowly weaned from cheap oil and gas.

Although bioresources alone will not shoulder the whole load of the resource change, they are pivotal for the structure of future industry. The reason for this is that they are the most flexible resources in society's future arsenal to ensure prosperity and sustainable development. They may be utilised for energy provision as well as for the provision of material goods and food; they may be readily stored and transported and finally there is ample experience how to process them. However, they pose some challenges that have to be met. Among them are relatively high prices, decentralised provision, low transport density (as well as high water content) and short shelf life compared to fossil alternatives. Meeting these challenges will transform chemical engineering (*4*). In particular, designing new industrial processes based on bioresources will require a much enlarged process concept, including raw material provision, logistics and by-product utilisation. Environmental and ecological optimisation will require innovative technology structures that are adapted to regional resources and markets, leading to a much more diversified picture regarding industrial processes. Finally, process engineers will have to employ innovative methods to design and optimise technical solutions to utilise relatively expensive and limited resources to their fullest potential. In the following, two particularly interesting aspects will be addressed: minimising the ecological pressure of industrial processes based on renewable resources, and maximising the economical benefit from a limited regional bioresource base.

Economy of Scale *vs.* Ecology of Scale Revisited

A particularly interesting aspect of the change in raw material base will be a reorientation in the scale of processes. Renewable resources for process technology have low transport density and/or high water content (see Table 1).

As a result, transport effort to 'the first processing site' will increase. One way out is a more decentralised industrial structure that puts processing plants closer to the fields and forests where bioresources are grown. This is especially important for processes that require large amounts of energy, like bioethanol production. A considerable advantage for commodity products from such processes compared to fossil alternatives can only be realised if process energy is also switched towards renewable sources. Economic as well as society pressures require that this process energy comes from sources that are on the one hand cheap and on the other hand do not compete with food production. This means that agricultural by-products like straw, lower grade biomass like grass and low-grade wood will be the energy sources of choice. In these cases the necessary transport of resources to the processing plant will become even more decisive as it applies to the raw materials as well as to the energy resources necessary to drive the process.

Table 1. Logistic parameters for different biogenic raw materials

Material	Humidity % by mass	Calorific value kWh/kg	Density kg/m³
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

A recent study about bioethanol production (for fuel purposes) (*5*,*6*) addresses the question of optimal size of processing plants. The study compares four different scales of production for fuel-grade bioethanol: 60 000, 10 000, 5000 and 1000 t/a. The 60 000 t/a scale represents the lower capacity boundary of installations currently pursued by the industry; it is supposed to be operated using natural gas as heat source and electricity from the grid (Austrian electricity provision mix assumed (*7*)). Economic data as well as material and energy balances for the 60 000 t/a case were taken from Friedl (*8*).

The three other scales are distinctly small-scale, decentralised installations. In these cases energy provision was supposed to come from bioresources that were either by-products (such as straw) or part of the crop rotation necessary to provide the raw material for sustainable ethanol production (corn or wheat). If these sources did not suffice to cover the demand of the process, the same energy sources as in the 60 000 t/a case were assumed. Transport was in all cases supplied by conventional, fossil-based transport means.

The processes for ethanol production at all scales follow state of the art technology, including grinding of the raw material, liquefaction, saccharification and fermentation, followed by a separation train of distillation and azeotropic rectification. Contrary to usual process schemes, no drying of the mash to distiller's dried grains with solubles (DDSG) is included into the processes at smaller scale (<10 000 t/a) for options where mash is not used for energy provision. The reason for this is that for decentralised production sites liquid mash may be transported to farms as fertilizer with a much lower energy demand than required for drying, making this option more advantageous at small scale, especially in the face of a volatile and narrowing global market for DDSG. For comparison, the 60 000 t/a case was also calculated without drying of the mash. The equipment, mass and energy flows for each scale were optimised using standard flow sheet simulation program IPSEpro (*6*).

Fermentation at different scales differs in its efficiency. Therefore, conversion rates of sugars of 85, 87.5 and 90 % for the 1000, 5000 and 10 000 t/a processes, respectively, were assumed. Detailed process mass and energy balances, costs as well as flow sheets for all cases and options can be found in the work of Friedl (*6*).

For the 1000, 5000 and 10 000 t/a cases, three different technology options for providing process energy were included in the calculations:

Option 1: Ethanol production in combination with a biogas combined heat and power (CHP) plant: heat and electricity from the biogas CHP plant is utilised for the ethanol production and surplus electricity is supplied to the grid. The size of the biogas CHP is chosen so that its heat provision exactly covers the demand of the ethanol plant.

Option 2: Ethanol production in combination with biogas production: in this case, biogas is directly utilised to supply process heat for the ethanol production. The biogas unit utilises only the mash generated by the ethanol process. Excess biogas (in the cases with 5000 and 10 000 t/a capacity) will be utilised to generate electricity *via* a small biogas CHP.

Option 3: Ethanol production combined with straw combustion: in this case process heat is generated by burning part (27–52 % for wheat or 15–28 % for corn, depending on the size of the plant) of the straw produced for providing the input for the ethanol fermentation. Mash is utilised as a fertilizer as described above.

The ecological pressure was calculated for the whole life cycle, including the agricultural production as well as all transport affected by the technologies. This includes the transport of raw materials and energy sources from the fields to the site of ethanol production as well as any necessary transport of residues from the site back to the fields. Transport was assumed to be carried out by tractors for distances up to 15 km, above that trucks (40 t) took over.

All options were evaluated economically as well as ecologically. The economic evaluation was a straightforward calculation of the cost of one litre of fuel-grade ethanol (using optimised and size adapted processes) including running costs as well as the investment cost (a pay-back time of 7 years was assumed).

The ecological evaluation was carried out using the sustainable process index, SPI (*9*). This index describes the aggregated ecological pressure of a certain process by the area needed to embed this process sustainably into the ecosphere, rendering a kind of 'ecological footprint'. The SPI identifies the area A_{tot} necessary to embed a life cycle, providing certain goods or service to the ecosphere. This area is calculated according to the following equation

$$A_{tot}=A_R+A_E+A_I+A_S+A_P \qquad /1/$$

The areas on the right hand side are called 'partial areas' and refer to the impacts of different productive aspects. A_R is the area required for the production of raw materials, A_E is the area necessary to provide energy, A_I is the area to provide the installation for the process, A_S is the area required for the staff and A_P is the area for sustainable dissipation of products and by-products. The reference period for these partial areas is one year. All material and energy flows exchanged between the life cycle to provide the goods or service in question and the environment will give rise to a corresponding area under the categories identified above. The SPI method is based on the comparison of natural flows with the flows generated by a technological process. The conversion of mass and energy flows into an area is based on two general 'sustainability principles':

Principle 1: Anthropogenic mass flows must not alter global material cycles; as in most global cycles (like the carbon cycle), the flow to long term storage compartments is the rate defining step of these dynamic global systems; flows induced by human activities must be scaled against these flows to long term stores.

Principle 2: Anthropogenic mass flows must not alter the quality of local environmental compartments; here the SPI method defines maximum allowable flows to the environment based on the natural (existing) qualities of the compartments and their replenishment rate per unit of area.

Whenever a life cycle produces more than one product or service (as most life cycles do), ecological pressures have to be allocated to them according to an allocation rule. In these case studies ecological pressures were allocated to all products produced on the agricultural land necessary to provide raw materials for the bioethanol production, regardless of the fact whether they were used directly in the process or sold elsewhere (*e.g.* crops in the sustainable crop rotation not utilised in the ethanol production). Allocation was based on the income calculated at market prices.

Fig. 1 compares economic and ecological performance of different options for corn as a feedstock. The upper area (shaded with lines) shows the range of the price in € per 100 L of fuel-grade ethanol. The lower area (in full

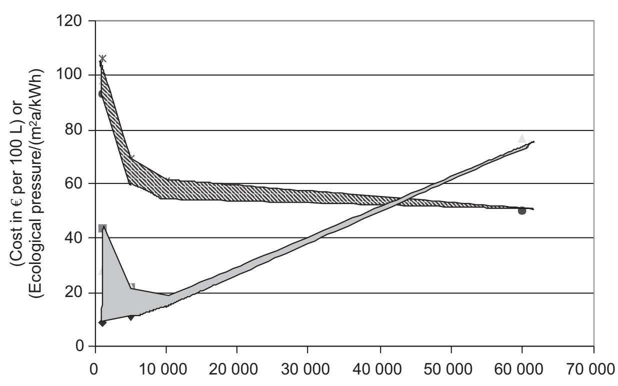

Fig. 1. Ecology of scale *vs*. economy of scale: ▭ ecological pressure of the options according to the SPI method in m²a/kWh heating value of ethanol, ▨ costs in € of 100 L of ethanol for the alternatives

grey) represents the range of the ecological pressures by different options.

There is a clear ecological advantage of biofuels compared to fossil competitors. All biofuels show a lower SPI than gasoline, which has an SPI value 60 % higher than the value for the 60 000 t/a installation (not shown in Fig. 1). The differences in the ecological impact of the various options are considerable.

There seems to be a large potential regarding the ecological impact when more small-scale production units are used: the best alternative (lower left corner of the grey area; option 1, 1000 t/a capacity) has only 15 % of the impact of ethanol from the 60 000 t/a plant. All decentralised options fare considerably better than the 60 000 t/a option, with the worst (option 2, 1000 t/a) still exerting only 45 % of the ecological pressure of the large-scale plant.

Particularly interesting is a look into the ecological performance of the different decentralised options at different sizes. The upper bound of the ecological pressure area is given by option 2, the lower bound by option 1, with option 3 in between. The large pressure of option 2 at 1000 t/a is due to the fact that for this small size the amount of mash produced by fermentation does not cover the energy demand for distillation. The reason for the consistent ecological advantage of option 1 is in the fact that besides ethanol this plant set-up generates electricity, too. This means that the resource is utilised for more than one product, distributing the pressure of the agricultural production on the two products.

Options 2 and 3 show that ecological impact decreases with the size of the plant. This is a result of the increasing efficiencies linked to larger production units. With option 1 the ecological pressure, however, increases with the capacity of the plant. This result is mainly linked to the fact that in this option the residues of the biogas unit are redistributed to the fields in liquid form, requiring intensive transport efforts. This, however, recycles important nutrients to a much larger extent than in the other two options (where only ash from burning straw is recycled in option 3, requiring much less transport). Consequently, the increased transport footprint is more than outweighed by the smaller impact as less fertilizer is required in this option. The higher transport to the fields with increased production capacity is responsible for the higher ecological footprint per kWh of ethanol produced.

An interesting aspect can also be seen in Fig. 1: at a capacity of 10 000 t/a, the economic and ecological performances of all three decentralised options become relatively similar and the influence of technology becomes less pronounced. The economy of scale, although clearly visible, has a less dramatic influence on economic performance than in the case of very decentralised structures. The 'ecology of scale', however, shows an increase due to the increased transport efforts. The higher ecological pressure of the 60 000 t/a plant is defined by its fossil energy provision as pressure from transport of low-grade bioresources to supply energy outruns the advantage gained by carbon-neutral process heat and power. This means that weighing 'economy of scale' *vs.* 'ecology of scale' new optima will be found: a sustainable industrial structure for utilising bioresources will show a moderately decentralised set of plants providing commodity products, still keeping transport from field to plant low but also taking advantage of efficiency increases with size.

From Plant to Technology Network

Besides decentralised availability, bioresources have additional properties and requirements that will strongly influence the industrial structure in the future. In fact, the basic resource for a bio-based society is fertile land, which can be utilised to provide different crops and forestry products as long as sustainability and long term fertility is granted by the agricultural practice employed. In many cases this will require well-balanced crop rotation systems and careful planning of the way land is distributed between fields, grass land, short rotation plantings and forests. The challenge, therefore, is less to utilise a single resource (*e.g.* corn) or the production of a single product (*e.g.* biofuel), but the most advantageous and still sustainable utilisation of the land at disposal for energy and material provision for society. This means that industrial planning has to be adapted to regional resource availabilities which include a diversity of crops (regarding sustainability of crop rotation) and resources such as wood and agricultural by-products. More than designing single plants, the engineering task will be to come up with integrated technology structures that utilise regional resources to serve regional markets for energy and commodities and optimise revenue from selling the products on global markets. The solution to this challenge will be regional multifunctional industrial centres.

Such a centre is characterized by generating energy carriers (*e.g.* biofuels) or services (*e.g.* heat or power) as well as industrial products based on regionally available renewable resources. Multifunctional industrial centres could either be linked to existing installations (*e.g.* a biomass heating unit serving a district heating network or an existing biogas plant) or conceived as a completely new installation.

A case study may exemplify this concept. The location of the case study in the south-east Austria features an existing biogas plant with corn silage and manure as an input and electrical output of 500 kW_{el}. Electricity is sold to the grid and heat is provided to a district heating grid. A furnace producer operates a research and development unit for chip and pellet furnaces which provide additional heat at the site.

Besides district heating, agriculture drying, production of wood pellets (from low-grade forest products or short rotation plantings) and utilising plant oil may be considered based on the raw material potential from 8 communities around the site (within approx. a 10-km transport radius that may be served by farm-owned transport means).

Process synthesis using the p-graph method (*10,11*) is employed to find a stable basic technology network, integrating the existing facilities and new technologies that utilise available resources. The main aim is to find a network consisting of operations of process technologies to transform raw materials into products (including energy). This method allows the optimization of process structures as well as energy and material flows. It is possible to factor in time dependencies regarding resource availability (*e.g.* harvesting times for renewable resources) as well as product or service demand (*e.g.* varying heat demand for district heating over the year). The input necessary for this optimization includes mass and energy balances, investment and operating costs for the technologies considered, costs for resources and utilities, prices for products and services as well as constraints regarding resource supply and product/service demand.

A generalized maximum structure comprising feasible technology pathways based on the resources from agriculture and forestry in the region was used in this project (Fig. 2). This structure includes all theoretical combinations of technologies linking regionally available resources and demands.

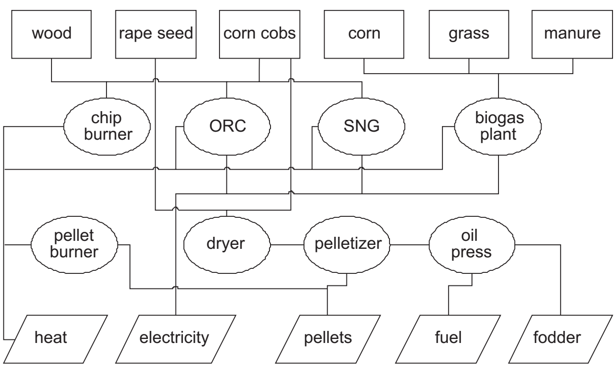

Fig. 2. Maximum structure of a regional multifunctional centre utilising wood, corn, grass, oil seed and straw; ORC – organic Rankine cycle, SNG – synthetic natural gas production

Based on the input data about flows and costs (variable and fixed costs according to the market prices in Austria in 2009), an optimal structure was generated. The goal of the optimization was to find a technology pathway generating the highest added value for the region. The optimum structure resulting from this optimization is shown in Fig. 3.

The optimal structure includes, besides the existing installations of the biogas unit and the furnace test rig, a synthetic natural gas (SNG) plant based on wood gasification with a Fischer-Tropsch synthesis. Heat generated by all plants is used for district heating and drying, providing dry wood for palletizing as well as dry corn for selling, depending on the season. The drying plant also handles rape seed, which is then used to provide fuel (in the form of plant oil) and fodder. The optimization proposes another biogas unit in addition to the existing plant.

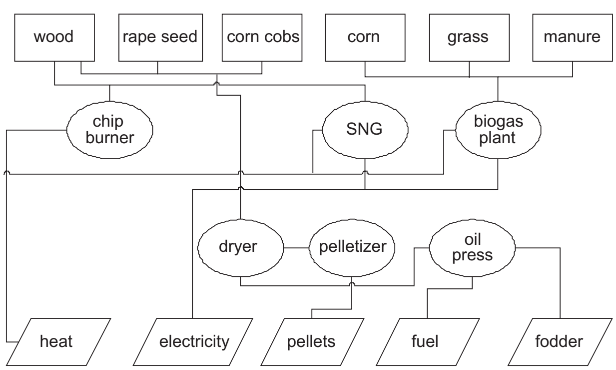

Fig. 3. Optimum structure of the given case study

Conclusion

Utilising bioresources will not only require innovative technologies but will have profound impact on the structure of industry in the 21st century. Efficiency will be a key to success in the face of limits to renewable resources. This will start with the choice of the right raw materials, where process industry will play out its high flexibility, allowing it to utilise raw materials not suited for food like straw and other agricultural residues. Utilising every part of its raw materials as it does now with fossil resources will become an imperative when using renewable resources. This will raise the challenge to construct 'bio-refineries' that will utilise raw materials from agriculture, forestry, aquaculture as well as biogenic residues from social activities (biowaste) and transform them fully into marketable products and energy services.

For the first time in 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. From chemical engineering point of view, there is a need 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.

Employing these tools to concrete case studies reveals that future industrial structure will become more decentralised. The reason for this lies in the decentralised provision of bioresources and their logistic properties, namely their generally low transport density and high moisture content. A new balance between the 'ecology of scale' and the 'economy of scale' will have to be struck: transport of the resources for processes and energy provision will have to be balanced against the efficiency increase of larger scale installations. The solution will be a moderately decentralised pattern of process plants providing commodities and more centralised sites for processes providing products generated from commodity input materials.

These decentralised industrial sites will have to be adapted to regional resource basis and will take the form of multifunctional industrial centres. These centres will be able to process various feedstock, tending towards regional markets for energy and commodities and optimising revenue from selling commodities on global markets as well as energy to grids (both electricity and gas grids).

From a strategic point of view, a stronger role of renewable resources as a basis for energy and commodities has multiple advantages: it reduces economic and political dependencies, increases added value nationally as well as in rural regions and effectively reduces human impact on the environment, if done properly. Implementation of such technologies, however, requires considerable restructuring of the economic and industrial structure, which takes time and is only possible if the right economic framework is provided to support this change.

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