

Utilising renewable resources economically: new challenges and chances for process development

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Abstract

In recent years a considerable increase in interest in the development of processes based upon renewable resources has occurred. One reason for this development is the call for more sustainable and environmentally benign production processes and products.

Increased utilisation of renewable resources, however, poses new challenges to chemical and process industries. These challenges arise from increased competition for renewable but still finite resources, the de-centralised production of the renewable resources and the complexity of the raw materials. These new challenges require new approaches to process development, as production systems become more complex and interlinked, logistical considerations become increasingly important and new technological solutions must be adapted to local and regional settings. As the structure of complex production systems must be newly developed and optimised, process synthesis will play an increasingly important role in process development.

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1. Introduction

Over the last 50 years chemical engineering became focussed on fossil oil and more recently on natural gas as its main raw material resources. Oil and natural gas replaced coal that acted as the primary source for chemical products during much of the 19th century up to the middle of the 20th century.

As a matter of fact, the raw material source shapes the structure of the industry that utilises it. With coal as a base of synthesis, the bulk production of chemicals centred around the big coal fields or along rivers that provided convenient arteries for the transportation of coal. Almost all synthesis processes started with the products from coal gasification, mainly via the Fischer–Tropsch synthesis. This required chemical engineering to start from fairly small molecules

and then build synthesis of more complex molecules on this small set of intermediaries.

The switch to oil in turn diversified both the raw material base and the choice of sites for chemical plants. As an ever expanding net of pipelines efficiently distributed crude oil throughout industrialised countries, refineries sprung up in locations that were closer to demand, especially demand of fuel. One of the advantages of fossil oil over coal is the much increased set of intermediary materials that can subsequently be used for chemical products. Refineries now act not only as major distribution hubs but also as a “switchboard” for materials by separating the multitude of divers materials contained in crude oil into a rich set of intermediaries for further treatment. Bulk products, like polymers (polyethylene, polypropylene), are produced close to these refineries. Other intermediaries, however, may be easily transported as they are predominantly liquid and distributed to chemical plants that are more free now to follow economical incentives like closeness to demand, good infrastructure and, increasingly, cheap labour.

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The switch to crude oil as the primary raw material source considerably invigorated chemical engineering. The diverse set of intermediaries that can be extracted with reasonable effort from crude oil allowed for a much richer roster of processes and products. Additionally, synthesis of complex materials could be started from more complex intermediaries. This reduced synthesis costs and added a boost of the chemical sector in the second half of the 20th century.

Crude oil, however, is a finite resource. Although there is no immediate danger that this resource will be completely depleted within the next few years (strategic reserves are estimated to be anywhere between 30 and 80 years), development of supply and demand of crude oil as well as the rate of discovery of new exploitable reserves indicate problems for this resource and all sectors based on it over the next one or two decades.

Fig. 1, from Schindler and Zittel [1], graphically depicts these problematic developments. As can be seen from this figure, actual crude oil production deviated from technically possible production around the time of the first oil shock in the early 1970s and has consistently lagged behind ever since. Following the path of technically feasible production, we would have already experienced the production maximum around 1990. As real oil production lagged behind the technically possible production, this production maximum must now be expected at a point around 2010. It must be stated again that this does not mean crude oil will be depleted by that time. However, prices for this resource will consistently increase as the increase in demand can no longer be offset by increasing production. A typical forewarning preceding such a situation are price fluctuations, since prices become increasingly vulnerable to anticipated influences on production capacities, a situation we already faced over the last years.

Fig. 1 also shows the mean of yearly new discoveries of exploitable crude oil reserves. It can be clearly seen from this figure, that there is a consistent decrease in the amount of new discoveries, adding to the overall picture of a finite resource at the height of its exploitation rate.

In the energy sector we have experienced a significant switch from oil-based fuels towards natural gas as a fuel,

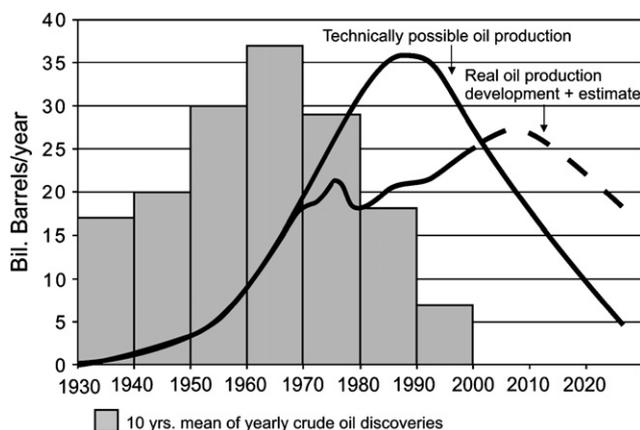


Fig. 1. Crude oil technically possible and real production over time.

especially in industry. This change has been driven by prices on the one hand but on the other hand also by environmental considerations, as natural gas has a significantly lower impact on global warming than oil or coal. However, the supply and demand pattern of natural gas follows that of crude oil with a delay of some 20 years. This means that a switch to natural gas as a resource for the chemical industry is an interim solution at best, buying time but not solving the underlying problem. Besides natural gas would require considerable restructuring of the sector, as pathways of its utilisation from the point of view of chemical engineering is closer to the utilisation of coal than that of oil. A switch back to coal seems to be impossible from the environmental point of view, as a much larger impact on global warming must be expected in this case.

Taken together the analysis of the current situation of raw material supply to the chemical sector implies a profound change of the material base of chemical industry within the next one or two decades. A leading contender to take the position of crude oil as the primary source of raw materials for chemical industries is biomass. This paper explores the implications of a switch to this “new” raw material base and the necessary changes in structure as well as technology that will be entailed by a wider use of renewable resources in the chemical sector.

2. Conventional renewable resources utilisation

Chemical engineering has a long tradition of utilising renewable resources. Research into processes utilising renewable resources for the production of a broader range of materials, from bulk chemicals (see e.g. Danner and Braun [2], Wachter et al. [3]) to polymers (Braunegg et al. [4]) and speciality chemicals (Eissen et al. [5]) has always been vigorous.

As a matter of fact, these resources have been almost exclusively linked to certain sectors within chemical industry, like pulp and paper industry, food industry and pharmaceutical industry, with the vast remainder of chemical processes firmly based on fossil and mineral raw materials. Generally speaking, renewable resources have been used in processes that either directly utilised agricultural products (like in the case of food industry) or where the product itself required their use (like in the pulp and paper industry).

In most other applications, renewable resources are faced with considerable economic disadvantages. These disadvantages come from the fact that under current conditions renewable resources (in terms of agricultural products) tend to be more expensive than fossil resources. This situation requires an added value for products from renewable sources, narrowing the field of possible products to those where special qualities may be achieved by renewable-based materials (e.g. in the field of high performance lubricants) or where the process itself requires renewable sources as input (as in many processes in the pharmaceutical industry).

In the field of bulk chemicals therefore, the use of renewable resources as a raw material base has therefore

been a distant second contender compared to fossil raw materials. Where they succeeded, as in the case of the production of ethanol as fuel from sugarcane in Brazil, other (strategic) considerations have played a major role in the decision to implement the processes.

From the technological point of view we can discern three different “archetypical” ways to utilise renewable resources.

2.1. Thermal treatment

Especially solid biomass (as wood) can be treated thermally by gasification or pyrolysis. With these technologies complex macromolecules in biomass are broken down into smaller molecules in gaseous or liquid state (with a remaining solid product containing ash and, dependent on the technology, solid carbon), which may subsequently be used as the building blocks for further synthesis, similar to the utilisation of coal. A major difference to the utilisation of coal is the higher oxygen content of the effluents which reduces the energy content of the resulting products.

As a general rule, these technologies require large-scale installations to be economically feasible. Gasification as a process for energy provision can now be seen as technically mature in a range from 5 to 200 MWe. Utilisation of the gas for synthesis of chemical products, however, still requires further research and development as the composition of the gases differs considerably from those generated by coal gasification, requiring different catalysts and process parameters.

2.2. Direct extraction of materials

One of the advantages of renewable resources is that they offer the chance to utilise the synthetic power of nature. This means that products like fibres, vegetable oils and fats as well as more complex products like essential oils, amino acids and proteins may be recovered directly from biomass without further synthesis steps.

This pathway is already one of the cornerstones for utilising renewable resources, both on large scale (like in the pulp and paper or the starch industry) and on small scale (especially in the field of fine chemicals production). As a general rule, existing processes are focussed on a single product with the main emphasis on high efficiency in extracting that target product. The rest of the material is degraded into low grade side products, in many cases utilised for energy provision (as in the case of pulp production), re-integrated into agriculture or downright disposed of as waste. This means that the target product has to pay for the raw material, the process and all subsequent steps like waste treatment and disposal.

2.3. Biotechnological conversion

Renewable resources offer an alternative synthesis pathway to the chemical synthesis of simple molecular building blocks to generate more complex materials: biotechnological conversion. In these processes biological agents take over

the task of facilitating the synthesis of products. These products may be as simple as ethanol or acetone or may be highly complex like antibiotics or proteins.

Although biotechnological processes generally run under moderate conditions, energy requirements for tasks like sterilisation, fermenter aeration, stirring and occasionally cooling might be considerable. Additionally, biotechnological processes usually work with aqueous systems and generate low product concentrations, at least compared with processes based upon fossil resources. This entails high energy requirements for separation and product conditioning, a task that is made even more complicated by the complex composition of the usual fermentation broths.

3. Challenges of reorienting processes to renewable resources

Within the current industrial system processes on the base of renewable resources are not inherently favoured. In direct competition, they usually are less attractive in economic terms. Although based on regenerative sources, they do not show intrinsic ecological advantages. As a matter of fact, there seems to be no indication that they should widen their field of application. Barring outside economic pressure (like increasing or fluctuating prices for crude oil), renewable resources do not seem to command the dynamic to alter process industries just by their intrinsic properties.

However, as crude oil will become an increasingly volatile and, in the end, scarce resource we might have to re-phrase the problem: it is not anymore interesting what changes will enable renewable resources to succeed in the competition with fossil resources; it seems to be more appropriate to investigate the challenges arising from a more central role of renewable resources in process industries. Some of these challenges that are especially important for further technology development are discussed in more detail in this paper.

3.1. The resource competition challenge

From the current point of view industrial processes offer a welcome pathway to utilise surplus agricultural products, thereby supporting the agricultural sector and boosting the development of rural areas. This is a reason that helped keep up the interest in research and development in this field and that drew support from public funds to renewable resource processes.

Even a modest increase in price or widespread insecurity about the development of the price of crude oil may change this perception profoundly. At the moment the process industry is a junior partner in the utilisation of fossil raw materials, especially oil. More than 90% of crude oil production goes into the energy market. It follows that the energy sector will be influenced at least as much as chemical industries by a change in the supply of oil.

With current prices energy provision technologies on the base of renewable resources are on the verge of becoming competitive with those based on fossil fuels. However,

strategic decisions on the political level begin to influence competitiveness of these technologies. The European Union set concrete targets for electricity from renewable sources (22.1% of the whole electricity market by 2010; European Commission [6]) as well as for biofuels (5.78% of the internal fuel market by 2010; European Commission [7]). As a result incentives for implementing renewable energy technologies have been adopted by many European governments. These incentives have already led to significant interest by investors in renewable energy technologies and a steep increase in corresponding projects is noticeable.

Products from forestry and agriculture are of course not the only source for renewable energy. Hydro power, wind power as well as solar energy as heat and electricity are obvious alternatives. However, biomass offers definite advantages for energy provision like storability and subsequently the possibility of continuous, season and climate independent energy provision. Additionally, many energy technologies can either utilise low grade raw materials (like wood chips) or may even be used as waste treatment (like biogas from municipal organic waste or manure). Nevertheless, a full scale switch of the raw material base away from fossil oil would exert considerable pressure on the supply of renewable resources from agriculture and forestry.

It is clear that any demand instigated by a change of the raw material base away from fossil fuels is an additional demand, on top of the current raw material requirements fulfilled by agriculture and forestry. As a matter of fact, both the energy sector and the chemical production will meet well-established industrial sectors on the market as competitor for the same raw material source. In the case of forestry, these are the pulp and paper industry, the construction sector and the fibre board production. In the case of agriculture, the main competitor will be the food sector.

Both agriculture and forestry still have considerable reserves in terms of production capacities. In the European case we currently witness a consolidation process in both sectors with the production concentrating on larger farms and forest enterprises. As a result productive land as well as forest areas that are disadvantaged either by location or by productivity are being taken out of production. Some types of land, e.g. grassland are increasingly becoming surplus areas throughout large parts of Europe, as land use pattern, agricultural technologies and consumer demand keep changing.

However, a simple comparison of the production of agriculture and forestry in Europe with the current demand of fossil oil clearly shows that even a partial substitution of crude oil will put considerable pressure on the markets (see Table 1, data from FAO [8] and Horn [9]).

It is clear from this rough comparison, that additional demand on agriculture and forestry to substitute fossil oil (let alone other fossil raw materials like natural gas or coal) cannot be covered alone by activating the reserves in both sectors. This in turn points to an increased competition for renewable raw materials. Within this invigorated competition the food sector (for agriculture) as well as the trade in saw logs (for forestry) pertain to markets with generally higher

Table 1

Comparison between products of agriculture and forestry with fossil oil demand (Data covering EU15 for the year 2002, Ref. [8])

Sector	Product	Production
Agriculture	Cereals (total)	214.6 [10 ⁶ t/a]
	Potatoes	47.2 [10 ⁶ t/a]
Forestry	Saw logs	135.7 [10 ⁶ m ³ /a] ^a
	Pulp wood	91.7 [10 ⁶ m ³ /a] ^a
	Wood fuel	30.3 [10 ⁶ m ³ /a] ^a
Demand	Fossil oil	775.8 [10 ⁶ t/a] ^b

^a Cumulative, including coniferous and non-coniferous wood.

^b Data from Ref. [9] valid for 1996.

product prices. This means that these demand sectors will, in a stiffer market, command high quality product segments.

From the point of view of technology development this insight into a future renewable resource market is crucial. In order to keep raw material costs in check, chemical processes and energy provision will have to concentrate on lower quality renewable raw materials. This includes surplus products (like grass, algae), harvest residues from crops that will go to the food sector (e.g. straw) as well as by-products and wastes from processes in the food sector (e.g. whey), from forestry or from society (e.g. waste cooking oil). Besides their low price, these raw materials offer the advantage that they have already been recovered from the land, so that costs and efforts for harvesting them will be low (or at least shared with more valuable products). High grade raw materials (like cereals) or specific raw materials (like herbs, fruits or specific animal parts) will remain reserved (at least with regard to process industries outside the food sector) for the production of high value goods, especially in the pharmaceutical and cosmetics sector.

3.2. The challenge to identify the right size and location for plants

Renewable resources will also challenge conventional wisdom about economy of scale as well as about optimal sites for plants. To begin with, contrary to crude oil, renewable resources are produced dispersedly and de-centrally. Whereas, in the case of crude oil, closeness to harbours or to pipelines defines optimal places for refineries and further processing of intermediaries is more or less independent of logistic considerations, processing of renewable resources requires careful reflection of the underlying raw material logistics.

In addition to their dispersed emergence, renewable raw materials are, in many cases, generated discontinuously, are perishable and require large transport volumes (or have low concentrations of the targeted material or are accompanied by large amounts of moisture). All these factors increase efforts and costs for transporting and storing raw materials, making raw material logistics a considerable part of process costs. This aspect becomes even more prominent in light of the considerations about the raw material competition described earlier: the process and energy sector will focus

on material flows of lower quality which in turn tend to have lower concentrations of interesting compounds, higher moisture content and low transport density. Furthermore, these materials are, in many cases, more perishable than higher grade raw materials like wheat, corn or potatoes.

All these factors add up to the necessity to re-think trade-offs for the decisions about size and location of process plants.

- Plant operating costs as well as specific investment costs tend to decrease with plant size (creating the “economy of scale”). In terms of transportation, however, larger plants mean larger raw material trading area and larger specific raw material transport costs. So there is a trade-off between the lower costs for investment and operation in the plant against the increase in specific transportation costs for raw materials.
- Another trade-off involves the decision between storage and campaign mode of operation. As many renewable raw materials are perishable, they must either be processed within their (short) shelf life or be stored. As raw materials from agriculture are produced discontinuously this leads to campaign modes of operation, in which the whole harvest is processed over a relatively short period of time and the plant is not operated for the remaining time of the year. Compared to a plant that operates continuously, this requires larger capacities meaning greater investment costs. The trade-off is now between costs for storage of raw material vs. the greater investment costs plus the costs for the downtime of the plant in the case of campaign mode operation.

Besides these trade-offs that have to be weighed when developing and implementing technologies on the base of renewable resources, the site itself needs careful consideration. Renewable raw material generation is spatially fixed which means that in order to reduce transportation efforts and costs, at least part of the treatment has to move “to the raw material”. Additionally, the structure of land utilisation clearly influences the raw material potential of a given region and hence the size and technology of processes utilising these raw materials. This results in a situation where size and technology have to be adapted to the structure of agriculture and forestry and more general, land use in a given region.

3.3. The process structure challenge

The previous argument leads to the conclusion that processes utilising renewable raw materials are more diverse than current fossil-based processes. In addition to the necessity to adapt plants to regional structures in terms of raw material potentials there are other factors that increase this diversity of technical solutions:

- Different crops may contain similar substances. This means that there will be processes adapted to the respective needs to treat different raw materials but still producing the same product in different agricultural

systems. This may also lead to “climate specific” solutions as varying crops may thrive in different climates.

- Different economic settings may require alternative utilisations even of the same raw material. Utilising grass under the condition of small-scale structured agriculture like in Austria will clearly differ from utilising it in an environment of large farms like in Denmark or the eastern part of Germany. Likewise the regional demand for products may favour alternative utilisations: demand for fodder in Denmark with an agriculture strongly oriented towards meat production may favour lysine production from grass juice, whereas lactic acid and amino acids may be the products of choice for Austria utilising the same raw material.

In addition to technological diversity, another aspect of the process structure challenge is the necessity for high efficiency in the utilisation of renewable resources. This necessity is demanded by tight competition for raw materials explained earlier. As current processes on the base of renewable resources focus on high efficiency to generate a certain target product, this “linear efficiency” will not suffice for processes in a fundamentally changed raw material situation. Processes will only succeed if they utilise the whole potential of the raw materials by generating not a single product but a set of products. This means that we will have to proceed from “value chains” to “value networks” that produce different products for various markets from a certain renewable resource.

The analogue here is the oil refinery, which generates different products for very diverse markets from a single raw material. In the end, the raw materials are transformed into valuable products or (energy-) services. Consequently, the processes that fulfil this requirement on the base of renewable resources are called “bio-refineries” (Kamm et al. [10]). One important feature of these bio-refineries is that they must flexibly change the utilisation pathways in accordance with the development of different markets. If we take the example of the “Green Bio-refinery” which utilises grass (see Fig. 2), the solid phase can either go into the fodder market or may be utilised as feedstock for a biogas unit to generate heat and power or it may be sold as fibre raw material. The decision must be based on the market and may vary in time as well as according to geographic setting. However, the flexibility

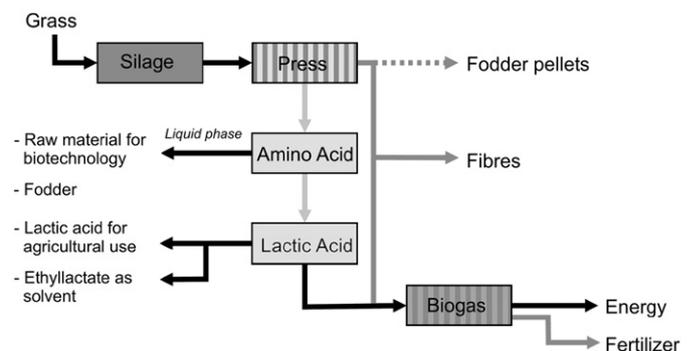


Fig. 2. Flow sheet of a “Green Bio-refinery”, Wachter et al. [3].

to enable the operators of such a technology to exploit those chances and optimise revenue according to the development of different markets must be provided by process design.

The example of the Green Bio-refinery may also be used to point out still another structural challenge for processes on the base of renewable sources. Keeping in mind that raw material logistics may play a major role for the profitability of processes, one has to address the question if all process steps must necessarily be concentrated at one site. Silage may be “outsourced” to farms where there is enough area to accommodate large silos. Pressing may either be done by mobile presses on the farm or centrally. Separation of amino and lactic acids may or may not be done at the site of the biogas unit. The decisions on the appropriate sites of the different steps are essential for profitability. This decision, however, is not only influenced by purely engineering concerns but has also to take into consideration the structure of the raw material supply as well as the interactions between different stakeholders to this process, that influence the different steps.

3.4. Technological challenge

In addition to the challenge to find the right process structure and constellation of stakeholders there are other formidable technological challenges. A prominent one among them is the challenge posed by the natural variation of quality of renewable raw materials. Raw material quality depends on climatic influences as well as on length of storage and geographical origin. It also depends on handling and optimal harvesting of crops and many other factors. Processes on the base of renewable resources must be very robust against changes of raw material quality if they are to succeed.

Another challenge arises from the increased importance of biological conversion steps. These steps, in general, operate with low productivities and concentrations of products in aqueous systems, leading to high costs for reactor investment and operation as well as high costs for separation. Development of selective, solid state, fermentation is still in its infancy but will become a necessity for many processes in the future.

Compared to fossil-based processes, the profile of the separation operations is vastly different in renewable resource processes. The dominance of thermodynamic separation processes like distillation and absorption will be challenged by separation processes that are more geared to separate complex, larger molecules. Especially membrane processes gain more and more importance and even more “exotic” operations like electrophoresis and chromatography are becoming widely used even in the production of bulk chemicals.

4. Process synthesis as a development tool

As formidable as the challenges are, the opportunities are also great. Over the coming decades there is the opportunity to fundamentally modernise the whole chemical industry sector and, develop it into a high-tech, sustainable backbone

of industry. However, this requires focussed and consequent process development based on sound engineering judgement. It is especially necessary to avoid “blind alleys” made attractive by exaggerated expectations for product yields and prices as well as underestimated costs.

Key to successful process development is the realisation, that there is never just a “production line” but always a “production network” when utilising renewable resources. From the very start of process development, this network has to be optimised in terms of overall economic results. As the structure of this production network itself must be optimised, process synthesis methods (Friedler et al. [11]) are becoming more and more interesting as tools of process development. A recent study about the Green Bio-refinery, adapted to the Austrian context in terms of raw material qualities and the structure of the underlying agricultural system (Halasz et al. [12]) has shown the potential of this tool: process synthesis allows not only to identify the optimal network for utilising green biomass but also to give invaluable information about the optimal mix between central and de-central process steps, development targets for specific technologies within the utilisation network and, last but not least, product lines that are currently not viable in economic terms.

5. Conclusions

Renewable resources offer an attractive way out of the impending economic and obvious ecological problems for the chemical sector over the next two to three decades. In recent years there has been marked increase of interest in this research and for the first time this interest is also articulated by large multinational companies. Reasons for this development are, on the one hand, the call for more sustainable and environmentally benign production processes and products. On the other hand, strategic considerations concerning the long-term price development of crude oil is forcing the chemical industry to reconsider its raw material base.

The most exciting aspect of this situation is, however, that the raw material source always shapes the technology and even more importantly, the structure of the industry that utilises it. This means that we face not only interesting new chemical processes but also a more fundamental shift in the structure of chemical processes. This shift poses new challenges to process development as we endeavour to utilise renewable resources in an economically sound manner.

Process synthesis will play a key role as a development tool for optimal “utilisation networks” on the base of renewable resources. It renders not only information on optimal process networks based on early economic analysis but will also provide important evidence to technology development targets. Further it will have to answer the question of what has to be done centrally and for what tasks will de-centralised processes be more convenient and how the structure of the whole process chain will be influenced by external influences like changes in the price levels of key products.

Modernising chemical processes in terms of making them more sustainable will be a major driving force for research and technology development over the next years. Meeting these new challenges will call not only for engineering creativity but also for including economic as well as ecological optimisation right from the beginning into process development; as well as breaking the conventional limits of processes in logistical and technological terms.

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