Renewable Resources – New Challenges for Process Integration and Synthesis

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The paper reviews the challenges and chances of process integration and especially process synthesis in the relatively new field of renewable resource utilization. Due to driving forces that are in many cases external to both technology and economics, this field puts new requirements on process synthesis in terms of methodology as well as interpretive power. Characteristics of the raw material sources but also new concepts like regionality and ecological structuring of processes gain interest in this context. These requirements are generalized from two particularly interesting case studies, the utilization of meat and bone meal and the "Green Bio Refinery Concept".

Process integration proves to be an important approach to keep costs in check in view of tight markets. Process synthesis is shown to be a central factor for both technology development and technology implementation in the context of renewable resource utilization.

The paper explores the scope of both concepts in terms of applications as well as requirements. It points towards necessary changes and additions to process synthesis methods in order to realize their potential in this field.

Keywords:
Process synthesis, process integration, renewable resources, sustainable technologies

Introduction

Renewable resources currently attract increasing interest as a "new" raw material base for industry out of many, mostly non-technical, reasons. Prominent among these reasons are environmental considerations or more general considerations concerning sustainable development. Features like "CO_2 neutrality" (meaning that products from renewable resources contribute less to global warming) and "biodegradability" (meaning that such products may be disposed of with less risk as well as at lower costs) are mainly responsible for the environmental attraction of renewable sources based technologies and products. Other reasons for increased interest in these technologies are their possible contribution to regional development (especially in the context of rural and disadvantaged regions) as well as their potential to support agriculture in times of surplus production.

A rapidly emerging topic is the increase of organic residues from agricultural production (like meat and bone meal) that either must not anymore enter the human food chain or must be disposed of in safe and profitable ways out of other (environmental) reasons. These mass flows pose in the first place an increasing waste problem but may be seen as chances for opening new sources to the raw material supply of industrial processes. The same holds true for structural changes in agriculture, where for instance large amounts of grass land will be either taken out of production or may form a base for industrial production due to altered agricultural production techniques as well as changes in consumer preferences.

All these factors amount to an increase in demand for industrial products and services from renewable resources. They also contribute to the broadening of the spectrum of available raw materials. This in turn puts considerable pressure on technological development of processes that utilize renewable resources.

It is against this background that the paper will analyze the role of as well as the challenges faced by process synthesis and process integration in technological development and implementation of new technologies and products. The hypothesis of this paper is that process synthesis may in this context have a unique chance to enter the technological development process as a central innovation tool as well as a major help for technology implementation. Process integration on the other hand will serve as a possible way to keep costs low and thus help these processes to compete in a market place currently dominated by products from other raw material sources, namely fossil resources like petroleum and natural gas.

Defining the problem

At first glance it seems to be ignorant to talk about renewable resources as something "new" to process industry. A number of well established industries never stopped using renewable resources as raw materials. Cases in point are of course the food and beverage industry, pulp and paper industry as well as industries based on natural fats and starch. All these industries are viable commodity producers that (at least on a cumulative base) handle mass flows in the same order of magnitude as chemical industry based on fossil raw materials. On top of this sectors like pharmaceutical and cosmetics industry convert renewable raw material into high price (but often low to very low volume) products.

Although all this is true, none of the above mentioned industries will be able to solve the problems that led to increased interest into renewable resources based technologies in the first place. On the one hand all the commodity industries cater to mature markets with little chance to expand their volumes in order to make use of additional raw materials. On the other hand high price sectors like pharmaceutical industry, although they might be rapidly expanding, are unable to put a dent in the abundant raw material offer that emerges in form of agricultural overproduction and organic residues. None of the mentioned industries offer the chance to answer to environmental considerations by altering the metabolism of society towards more sustainable patterns, meaning less green house gas emissions and more biodegradable waste streams. In addition none of the mentioned sectors have a considerable potential for positive impacts on regional development in disadvantaged regions.

This focuses the attention on sectors and processes where fossil (and in some cases mineral) raw materials have made major inroads at the expense of renewable resources during the last half century. This concerns areas as the energy sector (as the most prominent field) but also plastics, solvents, lubricants, textiles as well as fertilizers and textiles to name just a few important classes of products.

In all these sectors products from renewable sources are perceived to be "new". They have to compete with products that are well established on the markets and that are produced by processes optimized over the course of decades. They also face economical as well as logistical structures, technological experience and a standardization system that are determined and formed by the long (and successful!) use of products of fossil and mineral origin. The introduction of "new" technologies and products on the base of renewable resources therefore runs the gauntlet of institutional as well as economical and technical resistance by inertia.

Technological development under these circumstances is dependent on the following factors:

– early and solid optimization of technological pathways

– integration of economical as well as ecological considerations in defining these pathways

– highly intensified and integrated processes to keep down costs

– identification of "winners" along the production and consumption line in order to get hold on possible allies for technology implementation.

These factors are the base for looking closer into the possibilities of process synthesis and process integration in the context of development of processes based on renewable resources.

Important characteristics of renewable resources

Renewable raw materials have a number of differences that set them apart from "conventional" fossil and mineral resources. These differences have influence on the structure of technologies as well as on the socio-economic systems that link production with markets. It is therefore important to know about these differentiating factors in order to understand the challenges of developing and implementing renewable resource based technologies.

Decentralized raw material production

This is one of the most important features of renewable raw materials. Organic matter is produced either directly (in the form of plants) or indirectly (in the form of animal produce like meat, milk and manure) by utilizing solar radiation. The utilization of solar energy is inherently bound to area, making renewable raw materials decentralized resources.

This has important implications on the structure and size of processes and production facilities. Compared to conventional fossil and mineral raw materials that emerge from point sources like petroleum drill shafts or ore mines and that have relatively high transport densities, renewable raw materials always necessitate a certain (transport-)effort to collect them and make them available as raw material. Combined with the generally lower transport densities, this requires considerable transport efforts as well as large storage volumes for the same material input to industrial processes. This makes agricultural products and residues a typical "regional" resource, where processing has to be brought close to raw material sources. Contrary to the situation with conventional fossil and mineral raw materials, that can be hauled over long distances with minimal transport costs (at least at current prices), this decentralized nature and low transport density put clear limits on the size of industrial plants that process these resources. Whereas in the case of mineral and fossil raw materials there is the clear rule of "economy of scale" (meaning that the larger the plant the lower the production costs) this is not automatically true for processing renewable materials. Here a careful balance between the advantages of larger plants and the increased costs of hauling low density raw materials to the point of processing has to be cut. The factor of "regionality" of renewable resources is usually less important for agricultural commodities like cereals, potatoes or forest products like wood. The importance of this factor increases as more unconventional resources like grass or straw are involved. It becomes especially severe if residues or wastes are the resources in question.

This factor usually increases the unit production costs of products based on renewable sources. Besides this, it complicates technology development considerably. On top of finding the optimal flow sheet for processing a certain raw material, development has to include decisions on the right mix of central and decentralized steps in the process as well as the decision about the optimal size of all steps involved. This adds at least one more dimension to the "normal" technology development process.

Seasonal nature of renewable resources

Renewable raw materials are in most cases bound to the cycles of natural growth. This entails that raw material generation is an inherently discontinuous process, where times of abundance are followed by times where the raw material is either scarce or non available. This does not combine well with industrial processes that favor continuous production procedures in order to keep down the size of installations and avoid costly down times.

This results in the requirement for either storage of renewable raw materials (which are on top of their seasonality usually perishable, too) or for processes that can "digest" different raw materials (that may be harvested at different time). Again this factor complicates technology development and tends to increase costs of production processes on the base of renewable raw materials.

High raw material costs

Renewable raw materials usually are produced by agriculture, forestry, aqua culture or fishing. All these activities usually require intensive human labor and considerable application of machinery, making their products costly at least compared to mineral and fossil raw materials which just need the costs of mining and refining, processes that are done in large industrial scale with low labor costs.

On top of this general feature of being labor and cost intensive in generating, renewable raw materials are, as already mentioned, perishable. This leads either to the necessity of preservation (by applying cooling or chemical preservers) or to losses by degradation, further increasing raw material costs compared to conventional sources. The high raw material costs may only be offset by high yields, reducing losses during processing and generating valuable products out of all flows generated by the technologies utilizing renewable resources.

Complexity of raw materials

Plants and animal products are very complex materials. They do not only contain an enormous number of different chemical compounds, they may also be full of very complex chemical substances (like enzymes and special proteins) which are potent chemical agents for very different purposes. Besides they may be built up by highly specialized and versatile materials (like fibers) that by themselves warrant utilization of these raw materials.

This complexity is both a chance and a curse. It is a chance as by utilizing renewable raw materials we can build on the synthetic power of nature. This means that we can extract complex materials and substances from these raw materials that otherwise would necessitate considerable technical effort to produce. It is however also a curse as it complicates the task of separating different components of the raw materials, making down stream processing often costly and complex.

This feature of raw material complexity adds another dimension to the process of technology development. Materials and substances on different levels of complexity require very different technologies to recover them from raw materials or to synthesize them from precursors obtained from these raw materials. Not all these procedures are compatible with each other. That means that some pathways may be seen as parallel and compatible with each other leading to products that can be realized from one and the same raw material. Other pathways are not compatible leading to decisions which products to favor on the expense of others. Although this situation is also known to processes on mineral and fossil base it becomes more severe as the number of components in the raw material increases and as incompatibility of technologies becomes more prevalent as the technologies to treat renewable raw materials span the whole width from mild physical treatment to mild chemical and biochemical processes to thermal and intensive chemical degradation like gasification, caustic hydrolysis and combustion.

An interesting side aspect of this complexity is the issue of perilous components like microbes, viruses and other health hazards (as prions that cause BSE in cattle and possibly Creutzfeld-Jacobs Syndrome in humans). In order to make utilization of renewable raw materials safe, this "negative complexity" has to be taken into account. This mandates that certain precautionary technological steps (like sterilization or rendering) have to be applied to all material that is further processed. It is a challenge to find the optimal location for doing this in the course of complex process networks.

Examples for process networks based on renewable resources

At this point it seems appropriate to offer some insights to the scope faced by process integration and synthesis by means of to case studies. Although processes might differ widely according to raw materials as well as regional context the questions arising (to which process integration and synthesis might find appropriate answers) may be generalized from theses cases.

Case I Utilization of meat and bone meal[1]

Meat and bone meal is a major by-product of slaughtering a meat production. Until fairly recently meat and bone meal had been a valuable product used in agriculture as a protein source in animal fodder. The emergence of BSE (with its possible health implication for humans in form of Creutzfeld-Jacobs Syndrome) abruptly ended this pathway of utilization. Today and in the foreseeable future meat and bone meal is not allowed to enter the human food chain, transforming an abundant product into a huge waste problem.

Meat and bone meal is a material flow that emerges to the tune of at least 1 million metric tons in the European Union at the moment, hence it clearly is a bulk raw material on the base of renewable resources. In the current form of meat production, due to very high demands for meat quality from consumers, a considerable part of slaughtered animals (up to 50 % of the weight) actually ends in meat and bone meal or other waste from meat production. Currently this material has a "negative price" as slaughter houses, and by extension, farmers have to pay between 50 and 100 per ton for the treatment of this material, mostly by incineration. This puts a high economic pressure on agriculture in general. An optimized utilization process for this secondary raw material therefore is of high economical as well as hygienic priority in Europe.

From the point of industrial utilization meat and bone meal is an attractive raw material. As a by-product that currently puts considerable economic (not to mention ecological and hygienic) burdens on meat production it is available at reasonable prices. It contains fat, proteins and inorganic material (mainly apathit from bones) in considerable amounts and is relatively easy to handle.

A recent study on possible industrial utilization of meat and bone meal on the base of proven technologies came up with the following (simplified and not comprehensive) network of process (Fig.1)

As can be seen from Fig. 1 there exist an impressive multitude of products that might be obtained from meat and bone meal. The ways towards these products may be competitive or compatible. Although considerable technological information exists on most steps indicated here, no clear economic (let alone environmental) picture can be drawn on this information. It is therefore not possible to estimate the right "product mix" which is of course linked to an optimal utilization network. This clearly calls for process synthesis as a guiding instrument.

However, this is only one layer of application of process synthesis. Other concerns the hygienic aspects of utilizing meat and bone meal. Any material released from the processing network (regardless if product or by-product) has to pass a step that guarantees deactivation of prions (the cause of BSE). This might involve thermal or chemical processes. It is by no means clear at what step and with what kind of technology this task is optimally done in the different pathways. Here the issue of process integration meets process synthesis as this "security" step may double as a normal and necessary step in the process network, like in the case of total chemical hydrolysis.

Still another layer of applying process synthesis may lay in the fact that, as meat and bone meal is no longer a desired product, the whole chain of slaughtering and meat production merits renewed scrutiny. It might be possible to separate materials "at the source" (meaning in the slaughter house) in order to improve their value for industrial utilization. Again, a classical field of application for process synthesis methods.

This last point directly leads to a different set of applications. Utilization of meat and bone meal is clearly scattered among very different actors (with comparably different goals). These actors are linked to different sectors, from agriculture to food industry to chemical industry to the energy sector. It is an interesting task for process synthesis to allo-

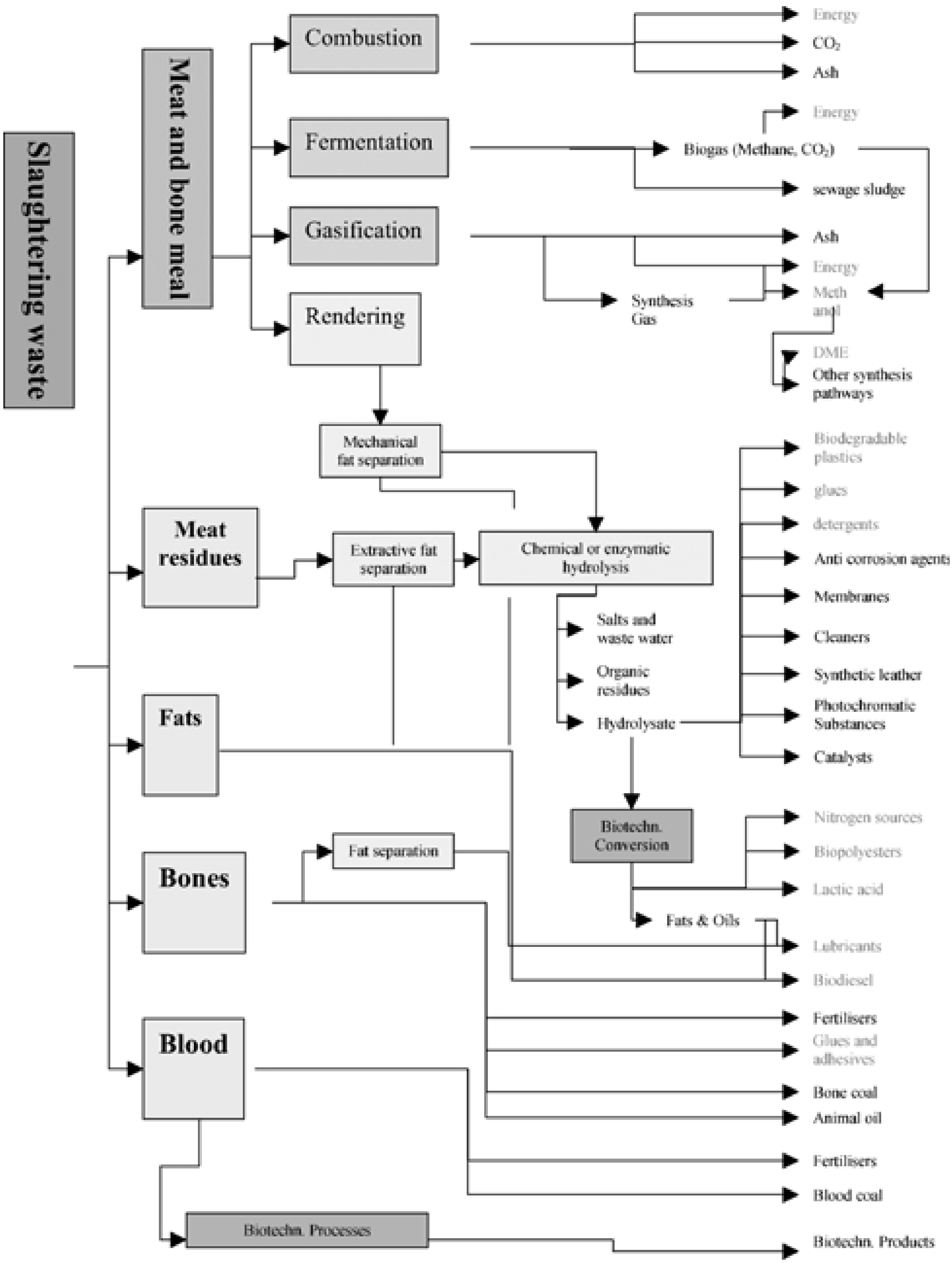

Fig. 1 – *Meat and bone meal utilization*

cate processing steps to these actors, given their different size and capacity as well as position in the processing network. On top of that it is of paramount importance for forming alliances between actors with the goal of implementing technologies to know about the burdens and benefits (in economics as well as ecological terms) that each actor might envision by implementing the technology network.

Case II. The "Green Bio Refinery"[2]

The concept of "bio refineries" calls for utilizing biogenic raw materials to produce a variety of (mainly bulk) chemical products.[3] Utilization of green biomass, as a special form of the bio refinery concept, is gaining interest out of reasons concerning agricultural development as well as landscape management. Green land in the form of pastures, meadows but also orchards are defining elements in many landscapes. However due to changes in consumer preferences as well as changes in agricultural production techniques green land is currently coming under increasing pressures. Over the next ten years up to 10 % of pastures may be taken out of use, with regional deviations that may be even more dramatic.

In general, this amounts again to a raw material source that can provide industrial raw materials in the order of several million tons per year across Europe. The loss of this element of landscapes may alter their appearance, leading to additional repercussions as landscapes form the basis for other sectors, especially tourism. Besides this the change in land use will also alter the structure of agriculture in many regions, adding to already existing pressures on this sector. Industrially utilizing grass and other green crops like alfalfa may therefore stabilize regional agricultural structures, preserve valuable landscapes and add to the economic development of rural regions.

The economic situation in this case however differs markedly from the case of meat and bone meal. Green biomass is an agricultural product that needs effort to be cultivated and harvested. Conservative estimates put the price of this raw material between 65 and 70 per ton dry matter which makes it a medium priced bulk raw material. The products of this process however have to compete with products from fossil raw materials which are based on raw materials that may be considerably cheaper. From the point of view of process development this puts high emphasize on optimality of process design as well as on full utilization of the raw material in order to create maximum value from the raw material.

Grass and other green crops offer a great variety of components as precursors for industrial production. It contains sugars, proteins and fibers as main components. Contrary to meat and bone meal however grass is a seasonal agricultural product, adding the problem of storage to the overall logistic aspects of renewable resources. Besides, grass has a comparatively low transport density which has to be taken into account in the structure of any processing network that is based on this resource.

There are many proposals for "green bio refineries" as concepts to utilize this abundant and possibly interesting resource. The differences between these concepts come from regional factors like regional markets, regional agricultural structures and the stake holders supporting these concepts. One example is the "Austrian" green bio refinery concept shown in Fig. 2. This is a concept that puts high emphasis on the preservation of cultural landscapes (as a basis for tourism) and that is adapted to relatively small structures in agriculture. Possible intermediary products from this brand of bio refinery are organic (mainly lactic) acid, amino acids and fibers. Each of these intermediaries offers several possible product lines which reach into various market sectors, from agriculture to construction to chemical products to name just the most important ones. Many of the possible product lines are compatible with each others however some of them (like protein extraction and lactic acid production) are competitive. The market values of possible products differ widely, with high prices for high quality proteins and polylactates and low prices for fibers. Energy production (via biogas) is also a possible form of utilization for either the whole raw material flow or residues from processes leading to other products.

This green bio refinery concept poses some interesting questions concerning process integration but especially process synthesis. Among the process integration questions is the integration of storage and chemical reaction. Silage is well known as a strategy to preserve grass and green crops. However it also produces lactic acid which in itself is a valuable and desired product. On top of that it also allows running all down stream processes in a continuous operation which might keep them profitable.

From the synthesis point of view this process network poses interesting and complex problems. There is the question of decentralized and centralized operations. What, given the low transport density of green crops, should be processed decentrally in order to save transport costs, what should be produced centrally? Another question is that for the optimal size of the installations. Again transport limitations will play a role in answering this question. Besides these more or less technical questions there is still the question of optimal product lines. Is it more profit-

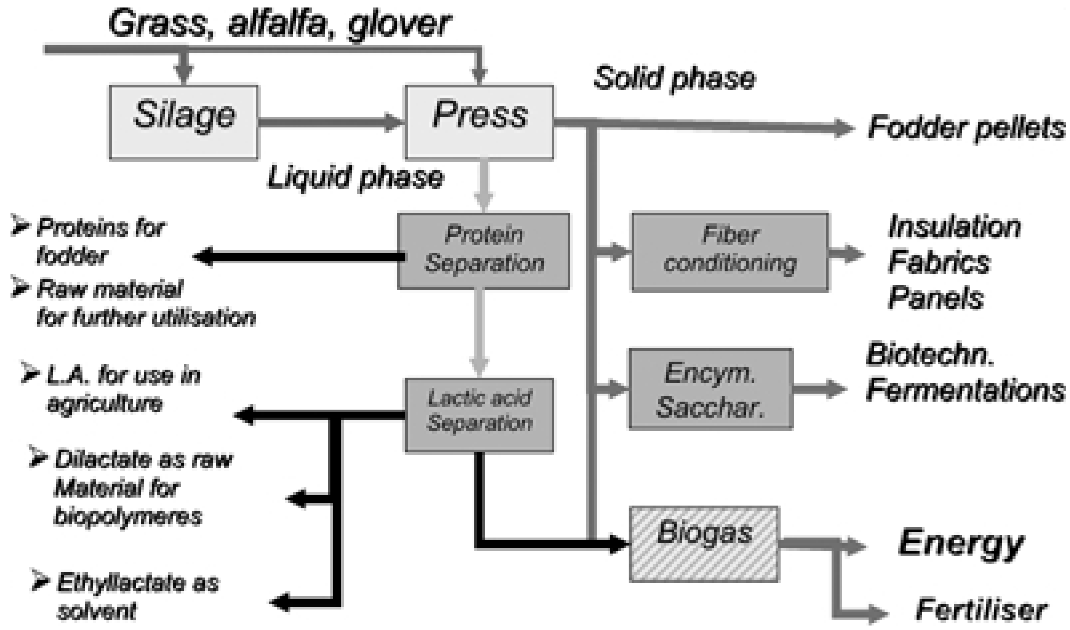

Fig. 2 – *The "Austrian" Green Bio Refinery Concept*

able to go for high price proteins or should lactic acid be preferred as a product? What are the optimal products generated from lactic acid in the light of available separation technologies and different requirements for product qualities, say in comparison between the production of ethyl lactate (as a bulk solvent) and polylactate? These are some of the many questions arising from this particular case study that might be answered by process synthesis.

The challenge to process integration

These particular properties of renewable raw materials pose challenges to process development as well as to the technical realization of processes. Let us first consider the challenge to process integration as a means to combine and intensify process steps within a larger process network.

From the property of regionality follows that industrial utilization of renewable raw materials tend to lead towards smaller, more decentralized installations. This means in turn that economy of scale can only be pursued up to a certain degree in order to reduce costs. This calls for process integration and intensification to take over the task of reducing production costs.

Particular interest in this respect must be directed towards integration of reaction processes into other process steps. Especially with the propensity of renewable raw materials to support microbial activity, biochemical reactions can in many cases support other steps in the process chain or can take advantage of them. One point in case is the integration of reaction and storage steps in the form of silage. In this case (as exemplified in the "Green Biorefinery Concept") the process of silage is utilized as storage step in which lactic acid produced from bacteria acts as a chemical preserver. However lactic acid is also a valuable product that is subsequently recovered from the stored grass. This is an example, where the long storage time (and the necessary volume of containers) is put to use to accommodate slowly progressing biochemical reactions.

Another chance for process integration is the combination of reaction and separation steps. This may take the form of membrane reactors where either biomass is retained (as a reaction catalyst) or volatile substances are separated via pervaporation from fermentation broths.

These examples are only a small sample of the possibilities to integrate steps in processing of renewable raw materials. The possible candidates for process integration are innumerable. With the economic pressure so intense as a result of high raw material prices and limited possibilities for processes to "grow into profitability" using economy of scale, process integration is a must for technologies on the base of renewable resources.

Challenges for process synthesis

Even more exciting than the challenge to process integration are the new roles of process synthesis for the utilization of renewable raw materials. Process synthesis may well prove to be indispensable for technology development as well as for technology implementation in the context of renewable resources.

Technology development

The development of processes on the base of renewable raw materials must aim at optimizing the "value added" to the utilization of a certain raw material not only by realizing high yields and efficient production of a certain product. These processes will only become profitable if they realize the whole potential of a raw material, utilizing it to produce different products on different levels of complexity. Thus, such processes are always process networks with many steps that may compete with or complement each other.

Here process synthesis may play a major role for systematic process development. It is of the utmost importance to obtain a clear overview of the different structures of "process networks" that may be employed to utilize a certain raw material. Given that these processes enter fiercely competitive markets, losing a potentially lucrative product or not investigating a potentially cost saving process alternative may make the difference between success and failure. Furthermore, the complexity of raw materials, the larger number of possible products for different markets and the multitude of technological pathways connecting raw materials with products do not allow to leave the choice of the right process structure to engineering experience and intuition alone.

The challenge for process synthesis methods in this context is

– To provide a complete and reliable picture of the possible process structures for utilizing renewable raw materials. The starting point for this task is the knowledge about the composition of the raw material (taking into account different levels of complexity of the substances and materials present in the raw material) as a base for the list of possible products.

– To indicate "crucial" steps in the utilization network, meaning steps that may decide (in terms of technical and/or economical efficiency) about the success of utilizing a certain raw material.

– To examine the influence of the technical and/or economical efficiency of process steps within the utilization network on the structure of the network as well as on overall performance of the technological system in general.

– To examine possible opportunities for process integration and intensification, as this is an important factor to keep down costs;

All this information is necessary to focus engineering research and development efforts. It will allow engineers to concentrate on these steps/technologies that are decisive for success. The result from process synthesis will also set clear goals for the engineering efforts as the necessary technological parameters for specific process steps will be made obvious.

Network Optimization

Utilization of renewable resources clearly calls for holistic optimization across the entire "network of utilization". The optimization (however sophisticated or successful) of neither single process steps nor production lines to single products will suffice in the face of fierce competition with well optimized products on other raw material bases.

It has already been mentioned in other sections that optimizing the utilization of renewable resources is a multi-dimensional task. This concerns both the target functions for optimization as well as optimization parameters:

– *Target functions:* It has already been stated that the reasons for increased interest for products from renewable resources mainly come from outside the economical sphere. Prominent among them are environmental reasons. This entails that the utilization of renewable raw materials must also be optimized according to its influence on the environment, besides the obvious economic optimization necessary to break into new markets. It is a truism that the choice of target functions has severe influence on structures of technological processes. This is not different in the case of technologies based on renewable resources. However the differences in structure (and hence performance) gain additional weight in this case. As a great part of the pressure to "switch" to renewable resources comes from other social arenas than the markets, the necessary trade-offs between economical and environmental optimization have to be laid bare to the eyes of decision makers. This is a necessary precondition for making the right decisions in the face of market forces and boundary conditions that do not favor implementation of renewable resource based products.

– *Optimization parameters:* Besides conventional optimization parameters (mostly coming from technology) utilization of renewable raw materials calls for additional dimensions of optimization. The most important issues here involve the question of optimal size of installations (given the "regionality" of renewable resources) and the question of decentralized versus centralized steps in the processing network.

These issues are admittedly new to conventional process synthesis. They require the inclusion of logistic aspects and transportation into process synthesis methods. However integration of these aspects is a 'conditio sine qua non' for successful application of process synthesis in this context

It is important to note that optimization and process synthesis are essentially seen as parallel activities that are intrinsically linked. Optimal processes are the only chance of implementing products from renewable resources in tight markets. Therefore it is important to apply optimization as early as possible in process development in order to focus on promising lines of utilization of renewable resources.

Technology implementation

This is a relatively new field for the application of process synthesis that gains importance in context with renewable resource use. Implementation of this type of products and technologies needs the co-operation of many and divers actors that must be identified at an early stage of process development.

The search for allies for the implementation of renewable resources based technologies is an especially important and complex task. As already mentioned, products from one specific raw material may cater to very divers markets as it involves materials and substances on different levels of complexity (from highly structured materials of construction to specialty chemicals to bulk chemical products) and diverse functionality. On top of this, many non-market actors may have a stake in implanting these technologies like regional development agencies, non-governmental organizations and farming associations. As technology development and even more so technology implementation is always a matter of committing serious money it must be made clear from the outset what actors can gain from implementing a certain technology or technology network. Lacking transparency of these gains is currently one of the most serious obstacles for development of renewable raw material based technologies. As actors are diverse and usually not aware of the potential of these new technologies and products for their own future development, they will not support their development, much less their implementation. It is therefore a new and innovative task for process synthesis to make these potentials visible and thus form a rallying point for new alliances for technology implementation.

Requirements for process synthesis methods

The field of renewable resource utilization offers unique chances to process synthesis. However it also has specific requirements that have to be fulfilled if process synthesis wants to realize these chances. These requirements concern both the methodological background and the interpretive power of these methods.

Methodological background

One characteristic of processing renewable raw materials is that in many ways it strongly deviates from conventional process engineering wisdom. That in a way reduces the appropriateness of heuristics that have been developed on the base of utilizing mineral and fossil raw materials. Renewable raw materials for instance offer biochemical treatment a much broader field of application than conventional process industry on fossil and mineral basis does. "Unconventional" process steps like membrane separations or chromatography play a much increased role in the utilization of renewable resources than in e.g. petrochemical processes.

For most of these "unconventional" technologies no or only rudimentary heuristics for their optimal application exist. This gives heuristics-independent methods (e.g.[4,5]) or at least methods that take into these new heuristics an edge over other process synthesis methods that employ conventional process technology heuristics as a basis for creating process structures.

Interpretive power

Any process synthesis method will only be successful if it really informs decision makers on many levels and in many sectors. Existing methods are already good at providing a (more or less) comprehensive picture of possible (and in some cases also optimal) technological structures for a given purpose. Their point of departure usually is the economical optimization of process chains. In addition to this (still important) feature some additional properties are necessary for success with renewable resource based technologies:

Inclusion of non-technical and non-economic optimization criteria

As mentioned in other sections of this paper driving forces for development and implementation of technologies for renewable resources utilization are coming from divers and often non-market actors. This requires that process synthesis caters to these audiences in addition to "conventional" technical and economic actors. In particular this involves two features that process synthesis methods must include to be successful as means to support development of technologies for renewable raw materials:

– Integration of ecological sustainability considerations in the construction of processing structures and processing networks.

As an important driving force for implementing products from renewable sources is their ecological advantage, maximizing this advantage is an important topic for technologies that manufacture these products. However as form follows function, processes that aim at ecologic advantages may differ in their structures considerably from such that pursue economic optimality. Besides this many heuristics currently employed in some process synthesis methods are based on economical considerations, again leading towards structures that are "economy-biased". Although integration of ecological issues is gaining importance also for other applications for synthesis methods this feature is of defining importance for their use envisioned here. The application of process synthesis methods in context with renewable resource utilization requires that ecological valuation must be included either in the heuristics employed or as target function for optimization or both. For this task highly aggregated and technology oriented valuation methods like the Sustainable Process Index SPI are already available.[6,7]

– Break down of economic and ecological valuation to the level of process steps

Processing networks for renewable resources are usually spread among different actors from a variety of sectors like agriculture and forestry, industry, transportation, and commerce, also including regional organizations. All these actors have differing, partly economic and partly non-economic goals. Especially technology implementation needs information about which actor will have what burden to carry and what the benefits are for the actors involved, both from the ecological and economic point of view. Only if these cost/benefit situations are clear for every actor it will be possible to identify lead actors for technology implementation and to negotiate the relation between actors necessary for successful co-operation in such (complex) processing networks.

Another general requirement (that is also shared by other technology sectors) is that process synthesis methods must be able to operate on preliminary technological as well as economic and ecological information. As process synthesis has to be seen as a tool for technology development it will always face incomplete and/or imprecise information. The most important strength of process synthesis from this view point is that it acts as structuring factor for technology development by putting the focus on those steps within a certain process chain (or process network) that merit further inspection as well as to put the finger on information that is crucially necessary for proper design and operation.

Conclusion

Development and implementation of technologies and processing networks on the basis of renewable resources is a new but promising field for process integration and process synthesis. Especially process synthesis may play a central role in the development process and may prove to be critical to technology implementation as well. Powerful process synthesis methods currently employed to "conventional" process industry offer a good starting point in this respect. These new chance however may only be realized if process methods adapt to the requirements of this new field.

From the methodological point of view it must be noted that many heuristics currently employed in process synthesis methods are either inadequate or need major revision when applied to process networks utilizing renewable raw materials. Heuristics--free methods (e.g. combinatorial methods) have here a clear head start. As ecological issues tend to play a significant role as driving force for implementing these products and processes, inclusion of reliable ecological valuation methods (as well as ecology based heuristics, when applicable) is a must. On top of that the space of optimization has to be enlarged in order to support decisions about optimal size of installations (in the face of trade-offs between transport and operating/investment costs) and about central versus decentralized process structures.

Especially in view of supporting technology implementation the explanatory power of process synthesis methods has to be improved. This involves particularly the description of burdens and benefits for actors within the processing networks both in economic and ecologic terms.

Notwithstanding the necessary methodological improvements application of process synthesis to the field of renewable resource utilization must be seen as a promising and particularly future-oriented area that merits considerable research efforts.

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