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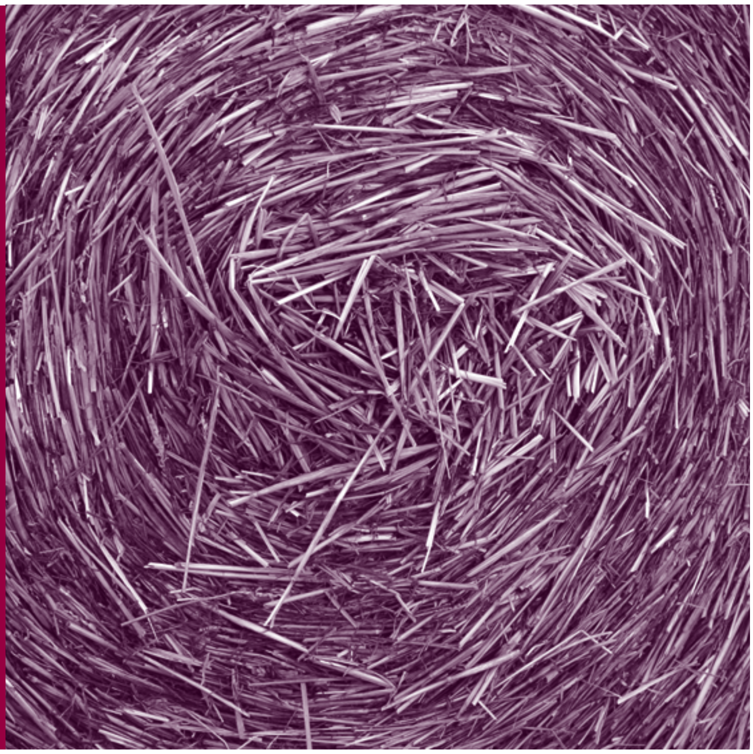
Industrial conversion of biomass

Summary



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SUMMARY

The chemical industry is displaying considerable involvement in the increasing resort to biomass. Although a range of products made of biomass (renewable energy resources) have already come onto the market in recent years (e.g. biodegradable packaging), this development is still in its early stages. Due to the great diversity in the conversion of biomass, complex questions are raised relating to technical feasibility as well as to the environmental and economic advantages and disadvantages of potential paths to the supply of products based on biomass.

An increased conversion of biomass in future could bring a number of advantages. These include, among other things, the replacement of finite, non-renewable raw materials as well as a reduction in import dependencies. The cultivation of biomass could in addition contribute to the preservation of biological diversity. Equilibrium in the balance in terms of CO_2 emissions is feasible using biomass, provided that the CO_2 released during (energetic) use corresponds quantitatively with that »taken« from the atmosphere during the growth phase. In addition, industrial conversion is normally followed by use as energy (cascade use). Furthermore, products developed from biomass have considerable potential for innovation – on the one hand in the further development of manufacturing technologies (e.g. for future so-called biorefineries) and on the other hand due to their specific properties (e.g. biodegradability).

The option of an increase in the (material) conversion of biomass is however not only being discussed against the background of the increasing scarcity of fossil raw materials and the as yet predominating conversion of biomass to energy. It is rather the vision of the sustainable, low-polluting and resource-conserving supply of basic chemicals and products made from these that is moving more clearly into the foreground.

The TAB report provides an overview of the various fields of research and application in the sector of the industrial conversion of biomass. This should serve to document the current status and prospects for the future. Both the analysis and the evaluation of the technical feasibility of an increased rate of biomass conversion have – when compared to the conversion to energy – been much less investigated. This discrepancy cannot be bridged with the present study, but rather only described as such.

The current conversion is central to the report. The conversion of biomass to energy is included in a comparative perspective. For one thing this should allow for a classification of conversion as a part of the total use of existing biomass resources, and for another thing should demonstrate the competition between the various possible applications for land and uses, as the quantities of biomass converted to energy today and planned for the future could have a limiting effect on overall potential.

In addition to the overview of processing methods for essential products made from renewable raw materials already practised today and planned for the future (on the basis of a literature analysis), an environmental evaluation for selected cases is put forward for discussion. In addition prospective approaches for biorefineries are analysed. Furthermore there is a discussion as to the extent bottlenecks might occur with the biomass available in the case of a clear expansion of conversion to material as well as energy. Finally, the market relevant aspects of products made from renewable resources are dealt with as well as open questions. The main focus of the considerations is on Germany.

ON THE CURRENT STATUS OF CONVERSION

The fields of application for renewable raw materials are already relatively widespread. The spectrum reaches from established procedures (e.g. manufacturing paper from cellulose) through niche applications (e.g. high-performance bio-lubricants, bioplastics) right up to applications currently being developed (e.g. composites made from thermoplastics and wood fibres or saw dust, so-called wood-plastic composites). It is the field of »new materials« in particular that is considered to be one of the most attractive future markets.

The market share of chemical base materials made from renewable raw materials is currently about 10% in Germany (in terms of the raw material base used). The most important groups are oleochemicals (tensides, biolubricants etc.) and chemicals (e.g. citric, lactic and levulinic acid, sorbitol, glycerine and cellulose derivatives). Approx. 2.7 m t of biomass is converted every year in Germany in the industrial, chemical-technical sector (chemical-pharmaceutical industry, paper industry, natural fibre processing industry). Of this, vegetable oils (0.8 m t) and starch (0.64 m t) made up the bulk of the raw materials converted for technical applications in 2005.

There are approx. 17 m ha of agricultural land in Germany, made up of approx. 12 m ha of arable land and approx. 5 m ha of grassland. Biomass was cultivated on about 1.4 m ha in 2005. The area of renewable raw materials for conversion under cultivation is about 0.28 m ha. Starch makes up the greater part of this in Germany (approx. 0.13 m ha), followed by rapeseed oil (0.1 m ha). Besides cultivated biomass, wood is also counted as convertible biomass, with no priority in presentation due to its for the most part already established uses, – with the exception of its constituent lignocellulose.

SOURCE MATERIALS AND ESSENTIAL FIELDS OF APPLICATION

Vegetable *oils and fats* are obtained under German climatic conditions primarily from (winter) oilseed rape, oil flax, sunflowers and mustard. Worldwide however, non-native oil grades, such as palm oil and »lauric oil« (coconut and palm kernel oil), at 27% make up of the bulk of oil production; with the addition of soybean oil this share increases to 52%. The importance of oilseed rape and sunflower oil at 17% is appreciably lowerer (for 2003). This is also reflected in the availability of vegetable oils in Germany: The greatest importance is accorded to rapeseed oil at 44% (1.4 m t), followed by palm oil (16%, 0.5 m t), which is exclusively imported, and soybean oil (14%,0.45 m t), which although admittedly produced in Germany, is however made of imported raw materials (2003). Consumption of vegetable oils for the manufacture of oleochemical products was estimated for 2003 at 330,000 t, with approx. 38% of which coming from indigenous cultivation. Linseed and sunflower oil and other oil-bearing seeds are primarily processed as soaps, paints and varnishes or are used in other chemical-technical sectors. It is mainly oilseed rape, and to a lesser degree sunflower oil, which have established themselves as sources of raw materials for biolubricants and oils. With the use of rapeseed oil in particular, the percentage of technical oils (including fuels) has increased considerably in proportion to edible and nutritional oils.

Starch in Germany comes mainly from potatoes (3 m t processed), followed by wheat (0.9 m t) and maize (0.6 m t). In 2004 approx. 640,000 t of starch were used for technical applications. The starch used is partly chemically unchanged, partly however also modified or degraded. Its specific properties are predominantly used as additives (e.g. thickening capability). Starch is among other things used as an additive in the paper industry and in detergents and cleaning agents, in the production of chemical base materials (e.g. tensides, stabilisers, organic acids), as a binding agent, in adhesives, in the manufacture of bioplastics (polylactic acid, PLA), as a bulking agent and in foams (e.g. packaging industry) as well as in pharmaceuticals.

Sugar is produced in Germany (and in the EU) from sugar beet; worldwide production relies more on sugar cane. Simple sugars such as glucose and fructose are used as industrial primary products, as are polymerised sugar and sugar derivatives. As polymer components and as derivatives, sugars are used in plastics (e.g. polyurethanes) as well as in tensides, in cosmetics, in detergents and in dyestuffs. In addition they are used as setting retarders (for cement/concrete, foundries), in adhesives/coating materials, as textile auxiliary substances as well as in the pharmaceutical sector. Sugar is converted e.g. into polyhydroxybutyric acid, biopolymers, citric acid or enzymes by fermentation. Furthermore, chemical base materials can also be produced from sugar, such as industrial solvents (e.g. polyalkylenglycol ether) or lactic acid and respectively its salts and esters. In addition sugar is used in the manufacture of bioethanol.

The most important raw materials worldwide for vegetable *natural fibres* are cotton, jute, flax and sisal. Due to the climatic conditions primarily flax and hemp are cultivated in Germany. German hemp production today is processed mainly for insulating materials with a smaller part made into fabrics for the motor industry. Natural fibres– with the exception of cotton and wool – have no practical role in processing in the German textile industry. Hemp is used industrially for strengthening fibres, flax is used in the textile industry (technical textiles), for hawsers, for ropes, as well as for roof coverings and as insulating material. Plastics strengthened with natural fibres play a substantial role.

Natural dyes are of secondary importance in Germany. The conversion to *proteins* currently only amounts to a comparatively small part of total conversion. Proteins are useful for the production of chemical base materials (adhesives, additives for manufacturing paper, binding agents for plywood etc.), for bioplastics as well as for encapsulating pharmaceuticals.

Wood is a renewable raw material, traditionally used in wood-working as well as in the paper and pulp industries. New uses of wood (constituents) relate for example to the use of *lignocellulose*, a mixture of cellulose and lignin. There are additional sources of lignocellulose in addition to wood: Elephant grass (miscanthus sinensis), crop straw, reeds, grass, but also waste materials (waste paper etc.). Lignocellulose can be used as fibre in building materials and in future in so-called lignocellulose biorefineries. In addition, fuels can also be extracted from lignocellulose.

PRODUCTS

The most important groups of chemical base materials from renewable raw materials are oleochemicals (tensides, biolubricants etc.), yet also chemicals such as citric, lactic and levulinic acid, sorbitol, glycerine and cellulose derivatives. The use of biomass in the chemical industry comes about both by chemical as well as by fermentative conversion. What is characteristic about the use of renewable raw materials in the chemical-technical sector is that output is comparatively low.

Tensides represent the quantitatively most important substance group, relevant amounts of which are today already based on renewable raw materials in the chemical industry. They are produced from both petrochemical (petroleum-based) and oleochemical (renewable resource-based) base materials (each with a current share of 50%). The raw materials for environmentally friendly tensides are vegetable fats and oils as well as low molecular carbohydrates. The advantages of tensides (and the detergents and cleaning agents made from them) based on biomass in comparison to synthetic tensides, include the fact that these are completely biodegradable in sewage relatively quickly, and are moreover kinder to the skin than petroleum products.

Biolubricants are produced on the basis of fats and oils, whereas here long-chain fatty acids are primarily used because of their better lubricating properties. The raw materials currently on demand in the market: rapeseed oil, and with a limited volume sunflower oil, are available in Germany. The »bottleneck« in raw materials supply is more in the first processing stage than in the oil mills: The capacity of the existing large-scale plants is to a great extent taken up with the rapidly expanding production of biodiesel. The use of biogenic lubricants and hydraulic oils – on the basis of their biodegradability – is ideal in environmentally sensitive areas (e.g. in forestry).

Bioplastics are polymers manufactured exclusively or partially from renewable raw materials, which are biodegradable in a relatively short time. Starch is the most important renewable raw material used for manufacturing bioplastics. Starch blends (plastic composites) are used for the most part. A further important synthetic polymer with thermoplastic properties and a »transparent plastic« is polylactic acid (PLA). These polymers can be used in the manufacture of films, fibres, coatings, adhesive dispersions, disposable packaging for foodstuffs, and as additives for other plastics. The so-called biodegradable materials are plastic-like materials. Manufacturing and processing the most different biopolymers or organic products is now technically possible; in practice this has so far however only been rudimentarily established. A substantial share of the developments in bioplastics, which have in the meantime also reached market maturity, are aimed at replacing mass plastics such as polyethylene (PE), polypropylene (PP) and polystyrole (PS) in short-lived applications such as packaging.

Natural fibres are at present used mainly in thermoplastic and thermosetting press-moulded parts, partly also in natural fibre polypropylene injection moulding. In addition to flax and hemp, exotic fibres (such as kenaf, sisal, jute, coconut fibres) and wood fibres are also processed. They are predominantly used for the interior finishing of motor vehicles. The natural fibre reinforced plastics also count as *natural fibre reinforced materials*. The so-called wood-plastic composites (WPC), which are for the most part made of thermoplastic plastics and wood fibres (and additives), belong in turn to these. This product group has no particular relevance in Germany. The main applications are seen in the building sector, in interior furnishings (furniture, flooring) and in the automobile sector.

Wood-based and cellulose insulation materials dominate *natural insulation materials* in Germany. Whereas the so-called short fibres are used more in the materials area, the long fibres are used in the textile industry. For example chemical fibres are produced from cellulose (e.g. Viscose, Modal, Lyocell). These are processed with synthetic fibres or each other to produce mixed fibres, with improved textile properties (e.g. influencing the strength of shape, drying time, susceptibility to creasing).

Paints and varnishes with a vegetable oil base only make up a small proportion of products manufactured from fats and oils (approx. 8% of the source materials are used here) in Germany. For the most part linseed oil is the raw material base. Sunflower or rapeseed oil only play a tangential role in Germany. Vegetable oils, cellulose and resin are used in the production of *printing inks*.

ECOLOGICAL ASPECTS

In statements on the ecological advantages and disadvantages of the products and procedures examined, a basic assumption seems to be that products manufactured on the base of renewable raw materials tend to »perform better ecologically« than those made of fossil raw materials. The life cycle assessment method is of use to make a statement that is well-founded and bears examination. It appears however that comprehensive balancing is extremely costly. Nonetheless it does represent a necessary first step towards an overall evaluation which as such still remains to be carried out, and in which subsequently economic criteria should also be included. In the present report, statements from available studies for three bioproduct groups already in use today – biolubricants, bioplastics and fibre products – are compiled in the usual categories found in a life cycle assessment:

With *biolubricants,* the comparison of the life cycle of oilseed rape and fossil hydraulic oil (petroleum-based), rapeseed oil exhibits distinct advantages in expenditure on non-renewable energy sources and the greenhouse effect. In the categories of eutrophication, ozone depletion and acidification, rapeseed oil has disadvantages, which are least pronounced however in acidification. An inconsistent picture emerges regarding the emissions of toxic air pollutants: There are advantages for biogenic lubricants with sulphur dioxide and diesel particle emissions, drawbacks with ammonia emissions. Nitrogen oxides show a slightly positive result.

An exemplary comparison of the life cycles of polylactic acid (PLA) made from cornflour and of polyethylene (PE) made from petroleum indicates broad ranges with reference to their environmental consequences for the various *bioplastics*. Thereupon, no *general* tendency can be established on the basis of available studies with regard to the pros and cons of renewable raw materials in comparison to their conventional counterparts.

The starting point for the exemplary life cycle comparison of *fibre materials and products* was automobile interior fittings made of hemp fibres and of acrylonitrile butadiene styrene (ABS). Taking different systems limits into consideration (e.g. with or without exploitation / waste disposal) there are only few clear, generalisable results: There are advantages for the products made of renewable raw materials only at the cost of non-renewable energy sources and the greenhouse effect. In all the remaining categories no generalisable statement can be made.

Classification of the results

The overall conclusion must be that the life cycle assessment statements presented in the report provide a comprehensible insight into the problem of evaluation. Differences in the results of the studies evaluated result in essence from different system limits. As a key statement for the product groups of biohydraulics and biolubricants as well as fibre materials and products, biomass tends to display advantages at the cost of non-renewable energy sources and in the greenhouse effect. Further generalised statements on the advantages and disadvantages of »products made from renewable raw materials in principle« in the field of conversion are not possible with the available data. Further research is required here.

The *efficiency per unit of area* can be called upon for a comparison of various products made from renewable raw materials. Through the relatedness of the differences »biogenic – fossil« (products made of renewable raw materials – conventional products) of the individual environmental effects on the area under cultivation (e.g. in inhabitant values per 100 ha under cultivation), statements on the efficiency of the land use can be inferred. For the most part distinct advantages are apparent for products made of renewable raw materials at the cost of non-renewable energy sources. A generalisable result relevant to the efficiency per unit of area over and above the three product categories mentioned above cannot however be inferred from the available data situation. In view of the foreseeable increasing shortage of land and different efficiencies per unit of area for the various renewable raw materials, efficiency per unit of area however remains a substantial evaluation criterion.

For a further improvement of the ecobalance of products made from renewable raw materials (use of the advantages ascertained) it is presumably necessary to optimise all of the individual processes throughout the entire life cycle. For example, a reduction of the NH_3 and N_2O emissions from agricultural production (for instance through a reduction of the nitric oxide fertiliser requirement to plant breeding and forms of cultivation) would also lead to improvements in the problematic categories of acidification, eutrophication and ozone depletion. Thermal exploitation should be arranged after conversion is completed, as this is frequently advantageous for the balance of the entire life cycle of products made from renewable raw materials (substitution of fossil energy sources). Composting on the other hand is associated with lower allowances and on a case-by-case basis with considerable emissions of methane. Biodegradability does not thereby inevitably mean environmental friendliness and by all means does not have to be the primary objective of product development; a longer shelf-life for a product which can be thermal exploited can be more meaningful in a given case.

FUTURE MATERIAL USE – BIOREFINERIES

Biomass could be processed in future in so-called »biorefineries«. The concept of biorefineries stands for the entirety of technologies for the processing of biomass right up to industrial intermediate and finished products. As a result, biomass should be converted in to an extensive range of products by integrated production – e.g. into feedstuff, biogenic materials, fuels, chemicals. The target is the fractionation and further processing of renewable raw materials into products, which are competitive and able to replace those products which at present are manufactured petrochemically. The visionary notion consists of the transfer of today's complex cross-linked and historically developed structures of coal and petroleum chemistry (so-called chemical pedigree systems) to biomass. Such cross-linked structures do not currently exist in a comparable way for biomass, although they are technically realisable in principle.

A technically analogeous workability of the same chemical elements is first of all assumed in principle for both fossil and renewable raw materials during processing or usability as a raw material. An essential difference lies however in the fact that petroleum is used in the quality in which it is extracted from nature, whereas renewable raw materials – mainly products of a metabolic process in agriculture – integrate the (prior) performance of synthesis from nature. Renewable raw materials can therefore be modified in such a way during their creation that they have already preformed certain desirable main products (so-called precursors) suitable to the purpose of the subsequent processing (e.g. through the selection of plants, breeding, genetic engineering, methods of cultivation).

In the first stage of a biorefinery, precursor-containing biomass undergoes a physical separation of material. The main and by-products are subsequently exposed to microbiological and/or chemical metabolic reactions. The follow-up products can then be further converted or processed in a conventional refinery. In the present report the green biorefinery system, the lignocellulose feedstock and the whole crop biorefinery as well as the two-platform concept systems are presented. These systems are in a very early stages of development.

Green Biorefinery (GBR)

In the green biorefinery, green »nature-wet« raw materials such as grass, alfalfa, clover and immature cereal can be converted into a variety of products such as feedstuff, proteins, fuels, chemicals and also products such as organic acids, amino acids, ethanol or biogas through microbiological fermentation. To do this the green biomass is separated into press cake (containing among other things cellulose, starch as well as other organic substances) and press juice (containing among other things carbohydrates, proteins, organic acids). With the green press juice, the focus is on products such as lactic acid and derivatives, amino acids, ethanol and proteins. Feed pellets can be produced from the press cake. These can also be used as source material for the production of chemicals, such as levulinic acid, or also for conversion into synthesis gas and hydrocarbons (synthetic fuels). A weak point in this concept is that rapid primary processing of the green biomass is necessary or the use of controlled silage (as the content of the material changes during storage). There are no pilot plants for green biorefineries to date. The first processing stages of a GBR are for example currently being prepared on the site of the Selbelang feedstuff plant (Havelland, Land Brandenburg).

Lignocellulose Feedstock Biorefinery (LCF Biorefinery)

In an LCF biorefinery straw, grass, wood residues from forests and cellulose-containing waste (e.g. paper) are used to manufacture three different types of products: In the *lignin fraction* adhesives, binding agents, fuels or chemical products are manufactured; in the *hemicellulose fraction* firstly thickening agents, and secondly xylose follow-up products (e.g. furfural and nylon) are produced; and in the *cellulose fraction*, fermentation products such as ethanol or lactic acid (including also levulinic acid) are extracted from glucose. Among the potential biorefinery concepts, the LCF biorefinery is probably the one most likely to prevail, not least as a result of the availability of the raw material base as well as the good market perspectives for potential conversion products. There is as yet no pilot plant here either. The utilisation of lignin is at present a weakness in the LCF concept: It is currently utilised either as a fuel, an adhesive or a bulking agent. The lignin scaffold also contains considerable amounts of mono-aromatic hydrocarbons, which could additionally be used. As yet it has not proven possible to further split lignin; work is continuing on the chemical-enzymatic splitting.

Whole crop biorefinery

In a whole crop biorefinery – analogous to the LCF biorefinery – products from the three lignin, hemicellulose and cellulose fractions can be produced from crop straw. Raw materials are rye, wheat, triticale and also maize. If the straw is gasified, products such as methanol or polyhydroxybutyrate(PHB) can be gained from the synthesis gas. The corn can be converted into starch and further processed into corresponding follow-up products (glucose, acetate starch, glucosamine, plastics).

The two-platform concept

A further approach is the combination of two concepts – the production and processing of sugar on the one hand and that of synthetic gas (syngas) on the other. The renewable raw materials are separated into two technical tracks (so-called platforms). The »sugar platform« is based essentially on biochemical conversions; the utilisation of which is dependent on the water content of the biomass. The »syngas platform« comprises thermochemical conversions (among other things the Fischer-Tropsch process) and focusses on the gasification of biomass and its by-products. In addition, further processes (such as hydrothermolysis, pyrolysis, thermolysis) are running, which can be linked with each other. What is disadvantageous about the production of syngas is the necessity of removing heteroatoms (oxygen, nitrogen, sulphur) as well as minerals from the renewable raw materials and the high energy requirements of these processes.

ECOLOGICAL ASPECTS – ECOBALANCE REVIEWS

On the one hand high expectations are set for biorefineries. On the other hand, there not only advantages, but also specific disadvantages that can be associated with the production and the use of renewable raw materials in biorefineries (e.g. the use of fossil fuels). The present information base for an ecological evaluation of biorefinery systems is very incomplete. Within the scope of the TAB project ecobalance reviews were nevertheless prepared for the first time to provide an initial classification of three biorefinery systems on the basis of information available today.

Ecobalance review: Green Biorefinery

The starting point for this balance is summer pruning which is pressed. The juice is primarily used for the production of lactic acid or lysine and the cake for green feed pellets. Proteins and a fermentation residue are also generated. Lactic acid or lysine replaces the same microbiologically produced product. The green feed pellets and a part of the proteins could be used as protein-rich feedstuff and would replace soya bean oil meal, the (imported) protein feedstuff. Proteins can still substitute for acrylates and tensides produced from non-renewable sources. The fermentation residue can applied be on agricultural areas as fertiliser (replacing mineral fertilisers).

Overall, when observing the selected concept of the green biorefinery in comparison to conventional production, significant disadvantages are only apparent for the green biorefinery concept in the use of fossil energy sources. The differences are less pertinent as regards the remaining environmental effects, although – depending upon the products manufactured or those which they replace – greater differences in the balances can also arise in individual cases. The green biorefinery concept observed has a relatively high energy requirement resulting primarily from the drying of the green biomass (for the production of feed pellets) compared with the less expensive production of soya bean oil meal. A role is also played by the fact that the products from the green biorefinery predominantly replace other renewable raw materials, which for their part often require relatively little fossil energy and have low levels of greenhouse gas emissions.

In a further step, as an alternative to the »green biorefinery« variant, consideration is given as to whether the green biomass could also be completely processed to feedstuff (»dry plant« variant)or to biogas (»biogas plant« variant). Then the feedstuff production in the »dry plant« is similarly compared in an ecobalance to the soya bean oil meal supply (area under soya bean cultivation). The »biogas plant« variant replaces electricity and heat generation using fossil fuels and the fermentation residue can in turn be applied as fertiliser (replacing mineral fertiliser). It is further assumed that the same quantity of the green biomass is used in each of the three variants. In the final analysis, its usage in the »green biorefinery« and in the »dry plant« could »save« agricultural land, namely the area under cultivation for the soya bean oil meal otherwise needed, as well as (to a lesser extent) the land required for sugar beet cultivation for producing lactic acid or lysine.

The area no longer required can now in turn »lie fallow« or be »used alternatively«. In the case of »fallow areas«, the disadvantages of the »dry plant« are more pronounced than the »green biorefinery« – compared to the use of the replaced soya bean oil meal – in the expenditure of fossil energy sources, in the greenhouse effect and in acidification (exception: lysine in the GBR). On the other hand advantages are apparent in ozone depletion. The alternative use of green biomass in the »biogas plant« shows advantages in the use of fossil energies, in the greenhouse effect and in ozone depletion; disadvantages are apparent in acidification and in the nutrient yield. Considered in relation to this, the disadvantages of the »biogas plant« in acidification and in nutrient yield are more pronounced; a clear trend in ozone depletion cannot be observed.

In the case that land is »used alternatively« it is assumed that land now free – in spite of the increasing competition for use – is not required for foodstuff and feedstuff production or nature conservation, but could be used for the cultivation of energy crops (extended scenario). The calculations for all of the variants considered show advantages for the biogenic option in the use of fossil energies and in the greenhouse effect, and disadvantages in acidification, in nutrient yield and in ozone depletion (exception: ozone depletion in biogas plant). The typical environmentally specific implications of the cultivation and use of energy crops are noticeable in the »biorefinery« and »dry plant«.

Summarising, the inclusion of the alternative use of land for energy crop cultivation results in distinct advantages for the green biorefinery in comparison with the other land use systems for green biomass in the use of fossil energies and in the greenhouse effect. During the evaluation of the »green biorefinery« system, a central evaluation question would therefore rather be that of land use as a part of the overall utilisation concept; a comparison of individual products (whether lactic acid or bioenergy is of more practical benefit) would consequently tend to be subordinated.

Ecobalance review: LCF and whole crop biorefinery

Main products of the LCF-biorefinery are tetrahydrofuran (a bulk chemical), ethanol and plaster, which replace conventional produced goods each with same amount. Lignin (as a constituent of straw) would be used as a substitute for plastics such as acrylonitrile butadiene styrene (ABS) copolymerisate. Feedstuff containing protein replaces soya bean oil meal; the fermentation residue is applied as fertiliser (replacing mineral fertiliser). During the survey of the processing of straw for the ecobalance, advantages were established from the processing in a LCF biorefinery for almost all of the environmental effects investigated (exception: ozone depletion). The saving of ABS plastic stands out, which – due to the relatively large quantities of lignin accrueing, requiring further processing – has relevance. The results remain true in their basic statements for the other replaced plastics, however the extent of the advantages can differ.

For the *whole crop biorefinery* it is assumed that initially only the straw portion is processed (special form of the LCF biorefinery), whereby the additional use of the cereal would theoretically be possible without great expense. The use of straw to provide ethylene, gypsum, proteins and fermentation residue in the whole crop biorefinery is on the whole cheaper than the production and use of the conventional products replaced (ethylene, ABS, gypsum, fertiliser, soya bean oil meal). Advantages can be recorded for the whole crop biorefinery in the use of fossil energy, in the greenhouse effect and in acidification. No clear trend on the other hand is apparent in nutrient yield and in ozone depletion. The substituted lignin-based ABS plastic has the greatest influence on the result here as well.

In a further step it is kept in mind here that the straw could alternatively also be used in a completely different way: The variants »Leaving the straw on the field«, »Use for production of biomass to liquid (BTL) fuel« and »Use in thermal power station« are compared as alternatives. Both biorefinery concepts display considerable advantages with the use of straw in all of the environmental effects investigated compared to the three alternative possible uses. What is essential here is the use of lignin: The statements made are only valid on the assumption that high quality plastics and synthetic resins are replaced as a result. When substituting less complex manufactured plastics, straw converted to energy performs as well as that in the biorefineries. When lignin is converted to energy, the direct conversion of straw to energy is preferable to that in a biorefinery. LCF and whole crop biorefineries therefore have interesting ecological potential. The biggest challenge for the future exploitation of this potential lies in the use of lignin as a material.

Conversion to energy

The biomass converted to energy as a share of total primary energy consumption today is still relatively small. In 2004 it was 333 PJ of a primary energy consumption of 14,438 PJ. Bioenergy makes up the largest share of the renewable energy sources however. The bulk falls to solid bioenergy sources – essentially wood. Biodiesel also rates highly in the provision of primary energy. Other solid bioenergy sources, such as straw or the fuel bioethanol and gaseous bioenergy sources (biogas, sewage gas and landfill gas). In Germany, mainly oilseed rape, wheat and – in smaller amounts – also sugar beet are grown as energy crops.

Studies on *Biomass potential for conversion to energy* show ranges of biomass potential for the supply of energy today, for 2010 and 2030 respectively (partially also thereafter). In the scenarios from the studies evaluated on the conversion of renewable raw materials, it is assumed that an increasing share of the energy supply will be provided by biomass by 2030. The results show that bioenergy will be able to cover between 8 and 14% of the primary energy needs in Germany by 2030, if endeavours to improve efficiency are pushed ahead with. This would more or less correspond to the share of the total German energy mix that hard coal and brown will probably have by then. From the studies the recommendation follows that biogenic waste materials should have a primarily stationary use and that the expected shortage of land calls for the cultivation of high yield energy crops on the available land in order to reach the goals (e.g. in primary energy requirements).

There are a large number of studies on the *environmental effectsof bioenergy sources* in comparison with their fossil counterparts – in contrast to industrial conversion. An analysis of selected studies reveals for all of the bioenergy sources from cultivated biomass considered – in comparison with fossil energy sources – both environmental advantages and disadvantages: Bioenergy sources show advantages in the consumption of non-renewable energy sources and in the greenhouse effect; disadvantages are apparent for the most part in ozone depletion, in acidification and during eutrophication. Here as well a decision in favour of one energy source cannot be compellingly inferred from this. However as soon as – based on a normative setting or a particular objective – the highest ecological priority is awarded to the reduction of the greenhouse effect for example, all of the bioenergy sources examined performed better than their fossil alternatives.

A production factor limiting the increasing use of bioenergy sources is the available area under cultivation. For this reason bioenergy sources are compared with their fossil counterparts, and in addition an area-oriented comparison is conducted among the bioenergy sources (from cultivated biomass). In the result it can be noted that bioenergy sources show advantages in the consumption of non-renewable energy sources and the greenhouse effect. A differentiation needs to be made for the remaining categories of activity between cultivated biomass and waste materials (cultivated biomass: disadvantages in ozone depletion, in acidification and eutrophication; waste materials: frequent advantages or smaller disadvantages). A comparison of bioenergy sources with each other shows that solid bioenergy sources tend to perform more favourably than biofuels, with gaseous bioenergy sources lying in-between. Moreover, an initial ranking of bioenergy sources is possible: Accordingly, bioenergy sources which could replace various fossil energy sources provide the greatest advantages or smallest disadvantages, when they replace coal. The least advantageous is the substitution of natural gas; fuel oil has an intermediate position.

AVAILABILITY OF BIOMASS

Ambitious goals have been set both for the supply of biofuels as well as for the consolidation of electricity and heat generation from biomass in Germany and Europe. Assuming that the supply of biomass for conversion also gains more importance in the medium term than it has to date, then land requirements will further increase if the land required is not potentially to be in competition with foodstuff and feedstuff production or lead to an import of foodstuffs.

A series of potential assessments is already available for the conversion of biomass to energy. Industrial conversion makes less of a difference unter current conditions. The demand for renewable raw materials and energy sources will in future – above all in the field of conversion to energy and supported here with political measures – accordingly develop dynamically. The industrial conversion will probably be more cautious in comparison and more in niche areas, whereby a future conversion in biorefineries – which will probably not make a significant difference until 2030 – could also play a role. The supply side as a whole (technical biomass potential) will be characterised by the increasing cultivation of energy crops on agricultural areas that become available. Indeed the influence of agrarian and environmental policy conditions (including organic farming) on biomass potential is strong, as is that of additional measures in environmental protection and nature conservation (for example the establishment of nature conservation and compensation areas, which may no longer be used for agriculture). However even with extensive nature conservation measures, an increase of the technical biomass potential can in principle be assumed (e.g. through more extensive conversion).

Varying competition for land and uses result from the potential development paths of supply and demand presented in the literature: *By extrapolating the prevailing policy conditions* a sufficient supply of biomass would be available both in 2015 and in 2030. Certainly intensified competition is to be expected for the (cost-effective) lignocellulose waste materials, as by 2030 a multitude of new technologies ought to be established, for instance for transformation into electricity and heat, in fuels as well as in chemical raw materials. As demand will probably not be sufficiently covered by waste materials alone, an increase in the significance of the cultivation of lignocellulose crops is to be expected.

The use of renewable raw materials will probably still be dominated by use as energy in 2015. Competing uses for waste materials could well have come about through a considerable demand firstly for electricity and heat generation, and secondly to cover raw material requirements of (by then potentially developed) LCF biorefinery (partial) systems. *Through the establishment of more far-reaching policy conditions* in the energy industry on the one hand and in agriculture on the other hand, the demand for renewable raw materials ought to have exceeded supply by as early as 2015. In so doing, the extent of the demand surplus depends decisively upon the policy conditions (e.g. EU fuels directive). If there is further promotion, additional demand for renewable raw materials will have to be covered by imports. Also from this perspective, waste materials or lignocellulosic energy crops will probably be attributed a greater value than today.

As a first approach for 2030, the qualitative assumption can be made that the effects concerning the competition for land and uses are comparable to 2015. This holds true, if it is accepted for example, that the demand for fuels is directed primarily towards waste materials (e.g. containing lignocellulose), because appropriate procedures for instance the production of synthetic fuels (BTL) and of bioethanol from them could have reached market maturity. Furthermore biogenic fuels, such as biogas, biodiesel and bioethanol from cultivated biomass, could also gain in importance. Due to the »technical diversity« probably then available for the conversion of waste materials, it is more likely to be economic restrictions which make a changeover to cultivated biomass necessary. Thus for 2030 – even if only existing policy conditions are continued – it can be assumed that waste materials will not be available in sufficient quantities to cover demand. There is a tendency to expect that the discrepancy between the demand for renewable raw materials and available biomass will increase. In this case the demand for biomass to be converted to material and to fuel would have additionally to be covered by the cultivation of energy crops.

Regarding imports that may be potentially necessary, the supply situation for renewable raw materials in the EU-25 shows an adequate supply in the medium term if the prevailing basic conditions are maintained, and a supply deficit if more further-reaching basic conditions are established. At the same time Germany not only represents a substantial biomass market in the European context, but is also a comparatively important supplier of raw material. In principle it must be noted that a binding common European policy on dealings with the renewable raw material base does not currently exist; a non-coordinated approach by the member states could lead in future to considerable flows of biomass being displaced through Europe.

THE ACTORS' VIEWPOINT AND MARKET ASPECTS

The penetration of the market with products made from renewable raw materials in most cases still remains far behind the technical applications possible today. A differentiation is made between products, whose present market position was reached with the help of selective measures (e.g. biolubricants), and those which to date have had to survive exclusively with the for example ecological advantages (and for the most part disadvantages in costs) on the market (e.g. bioplastics). A key barrier to a broader market launch of products made from renewable raw materials is their significantly higher price when compared to conventional (fossil-based) products. A further obstacle is the lack of information held by industrial and private consumers on the advantages of the latest products made from renewable raw materials.

The use of *biolubricants* has as yet been clearly restricted due to a low level of consumer acceptance or higher prices than conventional lubricants. Biolubricants currently have a share of about 4% of the total market. The Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) achieved a push effect primarily in the hydraulics sector through its market introduction programme (MEP).

Bioplastics currently have a market share of approx. 0.3% of total plastics production in the EU. In terms of sales this currently equates to a bioplastics share of barely 1%. Starch and starch blends currently make up about 85% of the whole bioplastics market. The major obstacle to the broader market launch of bioplastics is their significantly higher material price compared to mass (fossil-based) plastics. The lack of information on all user levels plays almost as big a role. It is not least the legal framework which in practice obstructs a significant market diffusion of bioplastic products (contradictory regulations for bioplastic packaging in the German Packaging Ordinance and the German Biological Waste Ordinance).

A comparatively large market for other products is that of *natural insulation materials*. Every year approx. 1.3m m^3 is used in Germany, which represents a market share of approx. 5%. In further fields of application – for instance in natural fibre reinforced materials, tensides and other chemicals right up to varnishes and paints – statements could indeed be made on future developments, though no market shares ascertained.

In contrast to this, the market for the *conversion of biomass to energy* is certainly to a great extent also a young market, which however especially through the creation of a favourable economic framework – e.g. through guaranteed feed-in tariffs laid down in the Renewable Energy Sources Act (EEG) for the production of electricity from regenerative energy sources or through an exemption from mineral oil tax – has developed an increasing dynamism over the last five years. When considering the conversion of biomass to energy, wood remains the most important raw material, especially for the generation of heat. Future market developments specifically in the fuels business are not as yet tangible. BTL fuels and ethanol from lignocellulose in particular are attributed as promising.

In the fuels sector, biodiesel (Pflanzenölmethylester) is rated as considerably more important than bioethanol at present in Germany, whereby attention should be paid to the fact that market volume in the bioethanol sector will probably grow appreciably over the next few years. The use of biodiesel today – to the extent that vehicles have appropriate clearance from manufacturers – is as a rule considered to be economical. On the other hand, the use of virgin vegetable oil as fuel – based on the necessary conversion of a conventional engine – as a rule only in motor vehicles used at relatively high capacity.

Biogas is currently principally used for generating electric energy, which can be fed into the national grid. Its use as a fuel would be possible in future, folllowing appropriate cleaning, whereby the market structures for this are lacking in Germany. A feeding of biogas into the natural gas network would be possible in future following cleaning to natural gas quality.

From the producer's point of view, clear basic conditions for the production and marketing of products made from renewable raw materials are called for. From a documented questionnaire survey among actors in the biomass product field, it can be seen that the attitude for the future is predominantly positive. Even if this does not apply to all sectors, the majority of companies and organisations have several economic pillars, so that a short term change for the worse in the economic situation of one application field can often be compensated through opposing developments in other fields.

Consumers

The increased use of products made from renewable raw materials is still not a matter of course in spite of a range of environmental advantages. The consumer's point of view on this is differentiated, as regionally restricted pilot projects on biopackaging for example make clear. Accordingly, consumers expect packaging made from renewable raw materials to exhibit functional and qualitative properties that are comparable to conventional packaging. Higher prices are most likely to be accepted if the quality is better or there is an additional use (e.g. organic carrier bags, which can also be used as organic bin liners).

Considered as a whole, a satisfactory variety of products is expected (choice between different product versions) which in turn assumes an accordingly large selection of products made from renewable raw materials. Environmental aspects do indeed play an important role, however these are only able to trigger a purchasing decision in a few instances if the price is higher. Health aspects as a rule also trigger positive associations. It is furthermore expected that information about the product is readily understood and complete (e.g. labelling) and that the products are available to the consumers. Emotional aspects and aesthetic values also play a part. What is striking is that in many cases there is lack of information on the part of the consumer in all of the segments named – from technical suitability (e.g. with biolubricants) through ecological advantages right up to sources of supply. For this reason consistent marketing by companies when distributing is indispensable.

Macroeconomic aspects

On the basis of scientific results which are available both for the conversion of biomass to energy and as material, it has not as yet been possible to comprehensively evaluate the economic effects in Germany. Certainly there are studies on the impact on employment and the fiscal effects of conversion to energy, however the results diverge appreciably. The fiscal effects of conversion to energy are depicted as controversially as impacts on employment. In particular the effects of the mineral oil tax exemption for biofuels on the public finances are judged differently. Moreover the influence of the EEG applies in a similar way to the cost of electricity for private households, in trade and in industry as well as the net debit resulting from this (e.g. private electricity customers). In other dimensions analysed (e.g. the effect on agricultural restructuring and incomes in agriculture, cost efficiency with regard to ecological targets, export opportunities) the picture is also less than clear. For this reason further research is needed surveying the macroeconomic effects of the use of biomass.

SPHERES OF ACTIVITY, R&D REQUIREMENTS, ENVIRONMENTAL AND FOLLOW-UP ANALYSES

The technical options for the conversion of biomass have not been exhausted to date. Possible spheres of activity for the development of their economic and ecological potential include:

> The determination of specific targets for the conversion of biomass: A »roadmap for material conversion« would be useful here to more clearly define targets and accordingly set priorities, e.g. in the form of research and development strategies.
> An improvement of the technical options for the processing of biomass as material: For this, research, development and demonstration need to be pressed ahead with in view of the specific immaturity of the development in selected fields.
> The further development and selective promotion of the key building block of the future industrial conversion of biomass from the biorefinery concepts: A great deal of further development is required concerning the interpretation of the basic concepts, technical options for implementation as well as corresponding pilot plants.
> The further development of specific procedures of conversion to energy, as these open a »technical connection« to material conversion for instance, via the production of synthesis gas or the manufacturing of ethanol (as a potential

platform chemical).

- The cultivation and breeding adaptations of plants: Appropriate trials and research efforts for conversion to material (content material) as well to energy (energy crops) would require development.
- The establishment of accompanying research, such as for instance, the carrying out of appropriately designed ecological and follow-up analyses: This could help to more precisely determine the importance of industrial conversion and prepare prioritisation in R&D as well as in promotion.
- The establishment of market and acceptance research for products made from renewable raw materials: This could contribute to breaking down reservations and thereby existing market constraints among manufacturers, users and consumers;
- A forward-looking analysis of the foreseeable competition for land and the conversion of biomass to material or energy to enable integration into a strategic orientation.
- An improvement of the database for the statistical recording of output and products: An industry-related collection of data and information would bring about more transparency and for another thing provide the necessary basis for the ascertainment of the macroeconomic effects.
- The registration of further indicators: For a comprehensive evaluation it would make sense to integrate the CO_2-avoidance costs as a balancing factor for selected product paths.
- The consideration of specific supply and cultivation conditions for imported biomass (environmental and social standards) in further evaluation concepts.

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