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Scenario Projections for Future Market Potentials of Biobased Bulk Chemicals

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Three scenario projections for future market potentials of biobased bulk chemicals produced by means of white biotechnology are developed for Europe (EU-25) until the year 2050, and potential nonrenewable energy savings, greenhouse gas emission reduction, and land use consequences are analyzed. These scenarios assume benign, moderate, and disadvantageous conditions for biobased chemicals. The scenario analysis yields a broad range of values for the possible market development of white biotechnology chemicals, that is, resulting in a share of white biotechnology chemicals relative to all organic chemicals of about 7 (or 5 million tonnes), 17.5 (or 26 million tonnes), or 38% (or 113 million tonnes) in 2050. We conclude that, under favorable conditions, white biotechnology enables substantial savings of nonrenewable energy use (NREU) and greenhouse gas (GHG) emissions compared to the energy use of the future production of all organic chemicals from fossil resources. Savings of NREU reach up to 17% for starch crops and up to 31% for lignocellulosic feedstock by 2050, and saving percentages for GHG emissions are in a similar range. Parallel to these environmental benefits, economic advantages of up to 75 billion € production cost savings arise.

Introduction

White biotechnology, the use of fermentation and enzymatic processes in industrial processes, is gaining momentum in the EU as it is receiving increased attention in industry and in government policy. It is generally anticipated that white biotechnology can play a key role for the cleaner production of bulk chemicals, as it is expected that it contributes to saving resources and reducing environmental impacts of chemical production and to exploiting biomass as feedstock for industrial and energy production.

By far, the largest amounts of organic chemicals are nowadays produced from petrochemicals. Important reasons for companies not to shift to biobased production are higher production costs and depreciated capital investments in conventional technology. However, white biotechnology is, according to EuropaBio (*1*), key to the competitiveness of Europe's chemical sector. In earlier analyses, Hermann et al. (*2*) concluded that many processes of chemical production using white biotechnology offer clear savings of (nonrenewable) energy use and greenhouse gas (GHG) emissions already today, and substantial further improvements are, in principle, possible for the future.

To estimate the total environmental and economic benefits that biobased bulk chemicals may generate in Europe, the future production in physical terms has to be estimated. However, such an assessment is highly uncertain because it is a long-term development with gradual implementation that is expected to be driven by increasing fossil fuel prices, increasing environmental pressure, and supply security considerations.

Although several studies deal with the possibilities of biobased and/or biotechnological chemical production, only very few estimates have been made about possible quantities of production, and most estimates are moderate; see Table 1. None of these estimates exactly represents the product group aimed at in this article, that is, biobased bulk chemicals and intermediates that are produced biotechnologically. A larger potential is seen in the biotechnological production of chemicals independent from the kind of feedstock (*3, 4*). Only a study of the U.S. Department of Energy (*5*) that formulates a vision—but no future market potentials—for a biobased economy comprises all biobased bulk chemicals until 2050, and targets for biobased chemicals are high with a market share of 10% in 2020 and 50% in 2050.

This article provides projections of market potentials for biobased bulk chemicals produced by means of white biotechnology in the EU-25. For simplicity, we refer to these products as biobased chemicals. A number of scenarios are used to describe the possible future development until 2050, thereby assuming benign, moderate, and disadvantageous conditions for biobased chemicals. In these scenarios, different assumptions are made about the EU chemical sectors over all economic development and the future oil and biomass prices. For each scenario, land use, energy savings, GHG emission abatement, and production costs savings of biobased chemicals are investigated.

Methology

Selection of Biobased Chemicals and Petrochemical Counterparts. The biobased intermediates and derivatives shown in Table 2 have been selected for the analysis based on the outcome of the economic analysis presented by Hermann and Patel (*11*), together with the assessment of experts from the BREW project (*12*). According to these assessments, the selected biobased products may be good candidates for gaining large market shares in physical terms, that is, the future production costs of these biobased chemicals are expected to be comparatively low, whereas the current production capacity of petrochemical equivalents is high. For each of the selected biobased chemicals, "reference petrochemicals" have been identified that are most likely to be substituted and that were chosen by experts of the BREW project; see Table 2. Hence, it includes implicit expectations on markets and technical properties of the chemicals in question.

Acetic acid, adipic acid, ethylene and *n*-butanol are chemical intermediates that are, nowadays, produced in relatively high volumes from fossil resources, that is, from about 1 (*n*-Butanol) to 19 ktonne/year (ethylene) (*13, 14*) ,and that could be replaced by chemically identical biobased compounds. In contrast, biobased polymers are either not produced petrochemically (PHA) or are produced in small to negligible quantities (PTT and PLA) (*9*). Consequently, it is assumed—based on expert opinion—that these polymers replace bulk polymers from fossil resources, that is, PHA replacing PE, PTT replacing nylon 6, and PLA replacing PS

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TABLE 1. Market Projections of Biobased Chemicals

kind of product	market share	year	ref
biotechnologically produced building blocks[a]	6–12%	2010	*1, 6* citing Mc Kinsey
biobased polymers	1.5–3%	2010	*7*
biobased solvents	12.5%	2010	*7*
biobased polymers	3–6%[b]	2020	*8*
biobased polymers	1–3%	2020	*9*
biobased polymers	4%	2020	*10*

[a] Not necessarily biobased. [b] Assuming a total demand of 70 million tonnes in EU-25.

TABLE 2. Selected Biobased Chemicals and Petrochemical Counterparts

biobased chemical	reference petrochemical[a]
PHA (polyhydroxyalkaonates)	HDPE (high density polyethylene)[b]
PTT (polytrimethylene terephtalate)	PTT, nylon 6
PLA (poly lactic acid)	PET (polyethylene terephtalate), PS (polystyrene)
ethyl lactate	ethyl acetate
ethylene	ethylene[b]
succinic Acid	maleic anhydride
adipic acid	adipic acid
acetic acid	acetic acid
n-butanol	*n*-butanol

[a] In most cases, one main reference petrochemical has been identified, although in some cases two different reference petrochemicals are considered to account for different target markets. [b] Either the polyethylene can be replaced by the biobased polymer PHA or the ethylene needed for polyethylene production can be produced from biobased ethanol.

and PET. Ethyl lactate and succinic acid are further examples of products that are not produced in large quantities from fossil resources. Ethyl lactate is an organic solvent that can, among others, substitute ethyl acetate on a large scale, and succinic acid is compared to maleic anhydride, which is mainly used for the production of 1,4-butanediol, polyesters, and tetrahydrofuran, for which succinic acid also can be used (*11*).

Determining Market Potentials. First, the technical potential of a biobased chemical is determined, that is, the potential to substitute a selected reference petrochemical as far as product properties allow. Second, the economic potential, that is, the economically viable part of the technical potential is estimated. Third, a diffusion rate, that is, the time path for achieving this economic market potential, is assumed, leading to overall market potentials for each biobased chemical.

For the technical substitution potentials, the future market demand of reference chemicals in Europe is projected, and following the substitution of this, demand by biobased chemicals is estimated. First, if a biobased chemical is to be identical with a common petrochemical product, then then technical substitution potential is 100%. Second, if a biobased chemical replaces a petrochemical product that is chemically different, overall estimates of experts participating in the BREW project on the suitability of a biobased chemicals for substitution were used.

The economic substitution potential is a function of the difference between the product values of the biobased chemical and the product values of the reference petrochemical. Product values are production costs plus profits, and they include variable costs, fixed costs, taxes, insurance fees, plant overheads, allowance for marketing, administration, and R&D, as well as a so-called capital charge representing depreciation and profits. These values were calculated with the a generic approach, that is, "an ex ante estimation of the economic viability of biotechnological processes for which pilot plant or lab scale data do not yet exist or for which process data are not publicly available" based on a small number of components (*11*). Calculations were made using nonscenario dependent data as presented in ref *11*.

For the calculation of economic substitution potential, two cases are distinguished. First, if a chemically identical compound is substituted, then the economic substitution potential is 100%; in case where the product value of the biobased chemical is lower than the product value of the petrochemical and otherwise, then it is 0%. Second, if a chemically different compound is substituted, then the economic substitution potential depends on the ratio between product values, the eligibility for a "green premium" and ease of implementation. A green premium means that a biobased chemical has ecological or functional advantages that lead to substantial substitution even if its product value is larger than that of its petrochemical equivalent. In this study, it is assumed that only end products (such as polymers) have such a green premium, whereas intermediates (e.g., acetic acid) have not. These green premiums are based on expert opinion, as they have not been proven or quantified for biobased chemicals. Also, biobased products that are difficult to implement have disadvantages compared to their petrochemical counterparts and, therefore, do not substitute these completely until their product value is much lower. It is assumed that biobased chemicals with rather different product properties than their petrochemical counterpart are difficult to implement.

Technology Diffusion. In consultation with the chemical industry experts in BREW, it has been assumed that it takes 30 y until the full economic potential is reached, if the product value of the biobased chemical is not lower than the depreciated production costs of the reference petrochemical. This implies that existing depreciated petrochemical production facilities are kept in place until their end of life. On the other hand, if the product value of the biobased chemical is lower than the depreciated production costs of the reference petrochemical, the time to reach the full economic potential is assumed to be 10 years. This means that the existing petrochemical production facility is shut down before its technical end of life. Finally, in case demand for chemicals grows fast and additional capacity is needed, the economic potential of biobased chemicals is assumed to materialize immediately because biobased chemicals do not compete with depreciated plants. Product values of petrochemicals are calculated as described in ref *11* and are based on process requirement described in ref *15*.

Scenario Assumptions. *Set-up.* Market potentials of biobased chemicals depend on many factors such as fossil fuel prices, other raw material prices, process technology development, etc.; see ref *9* for a discussion on the number

TABLE 3. Main Assumptions in the Three Different Scenarios

	LOW − bad conditions for biobased chemicals[a]	MEDIUM − medium conditions for biobased chemicals[b]	HIGH − good conditions for biobased chemicals[c]
fossil fuel prices	low (up to 30 US$/barrel)	medium (up to 66 US$/barrel)	high (up to 83 US$/barrel)
technological development	technology remains at current state of the art	future technologies are available from 2040 onward	future technologies are available from 2020 onward
biofeedstock costs	high (400 ϵ/tonne fermentable sugar)	medium (200 ϵ/tonne fermentable sugar)	low (70 ϵ/tonne fermentable sugar)
chemical market	no growth (0% tonnage increase per year)	medium growth (1.5% tonnage increase per year)	high growth (3% tonnage increase per year)
subsidies	no subsidies for biobased chemicals	no subsidies for biobased chemicals	subsidies for biobased chemicals (1 to 5% of product value)

[a] LOW: In this scenario, external factors are disadvantageous for the development and implementation of biobased chemicals and, therefore, expected market potentials are low. [b] MEDIUM: The conditions for the production of biobased chemicals are neither especially advantageous nor disadvantageous, and market potentials are anticipated to be medium. [c] HIGH: All assumptions favor the market potentials of biobased chemicals, which in turn are estimated to be high.

of parameters that influence the market potentials of biobased chemicals. Because these factors could evolve very differently in the next five decades, we investigate market potentials for various scenarios. Given the time required for the full development of most processes followed by gradual diffusion and replacement of the existing capital stock, a time period of 50 years for the analysis seems appropriate. We restricted ourselves to three rather simple scenarios and limit ourselves to the most important factors, Table 3.

Fossil Fuel Prices. Fossil fuel prices influence the production costs of bulk chemicals in our calculation as fossil fuels are direct inputs for the production of bulk chemicals and are inputs for the production of utilities and intermediate chemicals. Projections of future fossil fuel prices vary largely with respect to time frames as well as price levels. For example, the US Department of Energy estimates crude oil prices to be in the range of 40−65 US$/barrel in 2005 to mid 2006 (*16*), and in 2005 the investment bank Goldman, Sachs projected very high peak prices of 105 US$/barrel in the short term. The World Energy Outlook (*17*) estimates that in the next couple of years after 2004, crude oil prices will drop below 30 US$/barrel, while the “high oil price scenario” assumes a price of 35 US$/barrel until 2030. In this study, we used the fossil fuel prices from the Message model, which is one of the models used for the IPCC SRES scenarios to estimate future GHG emissions (*18*) and which contains fossil fuel prices projections.

Technological Developments in White Biotechnology. In ref *11*, different data sets describing state-of-the-art technologies as well as future technologies for the production of biotechnologically produced chemicals have been developed and are used in this study. Future developments of technologies comprise improvements of bioprocess steps, product separation and purification.

Biofeedstock Costs. In this analysis, fermentable sugar is assumed as feedstock for biobased chemical production by fermentation. As for fossil fuel prices, the prices of fermentable sugars also may vary widely. In the HIGH scenario, a low sugar price of 70 ϵ/tonne is assumed, which approximately represents sugar prices in Brazil in 2000 and was the lowest price level worldwide. Thus, this scenario represents a “free” sugar market without trade limitations and without limitation of agricultural land availability or, alternatively, the location of the fermentation plant in a tropical country producing sugar cane. In the MEDIUM scenario, a sugar price of 200 ϵ/tonne is assumed. This is about the price of sugar in the US in 2000. It is lower than the current sugar prices in Europe due to better production conditions and ample availability of land in the U.S. Finally, in the LOW scenario a very high sugar price of 400 ϵ/tonne is assumed. This is beyond the average sugar price from starch crops (300 &ϵ/tonne) in Europe and could be reached as a consequence of competition for agricultural land with the production of bioenergy and/or as a consequence of agricultural policy that prevents the decrease of sugar prices.

Chemical Market. The starting point for projections of the demand for petrochemicals is the production volume of reference petrochemicals of the selected biobased chemicals in 2000 in the EU-25 based on ref *13, 14,* and *19*. Using a variety of sources (*20–22*) we also estimated the total production of all organic chemicals in EU-25 in the year 2000 at approximately 70 million tonnes.

The production of chemicals in Europe depends on the global chemical demand, which in turn is influenced by the overall economic development. Furthermore, the production in Europe is also influenced by the competitive position the European chemical industry achieves. Based on discussions with experts in the BREW project, a low growth rate of 0%, a high growth rate of 3% per anum (p.a.) and a medium growth rate of 1.5% p.a. were assumed. These projections are within the range of projection from other scenario analyses (*11, 23, 24*). As a consequence, the total production of all organic chemicals in 2050 is projected to amount to 70, 150, and 300 million tonnes in the LOW, MEDIUM, and HIGH scenario.

The total production of the selected chemicals—i.e. bulk chemicals that may be replaced by white biotechnology products from biobased resources in EU-25—was about 31 million tonnes in the year 2000, representing nearly 50% of the total production of all organic chemicals. Hence, for the three scenarios, the total production of the selected chemicals in 2050 is projected to amount to 31, 65, and 136 million tonnes in the LOW, MEDIUM ,and HIGH scenarios, respectively.

Subsidies. To include possible policy stimulation of biobased chemical production, direct subsidies are taken into account in the HIGH scenario. However, the level of subsidies assumed is very low; between 2000 and 2050 assumed subsidies decrease from 5% to 1% of the product value.

Results

Market Potentials. The market potentials for the three scenarios are depicted in Figure 1. The lower part shows the biobased products, produced by white biotechnology. These increasingly substitute a share of the selected organic chemicals that are listed in Table 2. The selected organic chemicals are approximately half of all organic chemicals,

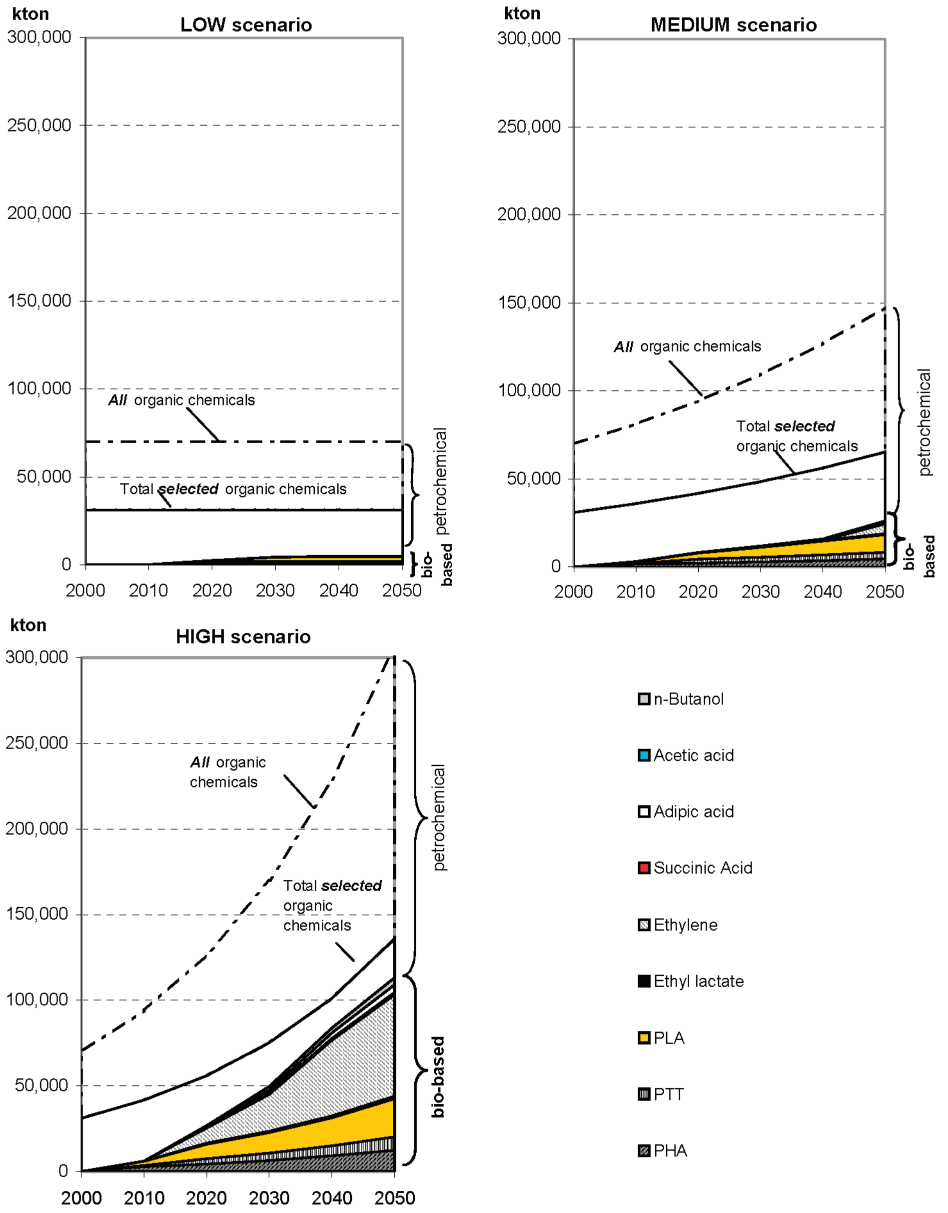

FIGURE 1. Market potentials of biobased bulk chemicals in the EU-25 for the three scenarios for the years 2010−2050.

which are represented by the upper, broken line in Figure 1. The total volumes differ significantly across the scenarios. whereas in the LOW scenario in 2050 only about 5 million tonnes of biobased chemicals are produced, the respective values for the MEDIUM and the HIGH scenario are about 26 and 113 million tonnes. In the HIGH scenario, the total demand for biobased chemicals is, hence, about 20 times higher than in the LOW scenario. Part of this large difference can be explained by the difference in the total market demand for chemicals. Another part is due to advanced technology and differing raw material prices that result in a better economic performance of biobased chemicals.

In the LOW scenario, PLA has the largest market potential, and PTT and PHA also have relatively large potentials. The product values of PLA and PHA are higher than those of their petrochemical counterpart, that is, these products enter the market only on behalf of the “green premium”. In contrast, PTT is competitive compared to PS, and it is at the edge to competitiveness compared to petrochemical PTT. Minor quantities of ethyl lactate and of succinic acid enter the market as a consequence of the green premium.

Also in the MEDIUM scenario, the most important potentials are those of PLA, PHA, and PTT. Throughout the period studied, PLA and PTT are economically slightly more viable than some of their petrochemical counterparts. PHA becomes economically viable only between 2040 and 2050 but enters the market in noticeable quantities already in 2010 due to the green premium. In 2040–2050 biobased ethylene also becomes economically viable and is produced.

In the HIGH scenario, several other white biotechnology products enter the market in addition to PLA, PTT, and PHA. Most importantly, ethylene is produced in very substantial quantities from 2030 onward. At the end of the period adipic acid, *n*-butanol, succinic acid, and ethyl lactate also contribute to the overall potential, but the quantities are relatively low. The product values of all biobased products are lower than those of at least one of their petrochemical counterparts from 2020 onward. This means that the green premium does not contribute significantly to the market development in the second half of the HIGH scenario. The total shares of biobased chemicals in 2050 range from 15% in the LOW scenario to 40% in the MEDIUM scenario and 83% in the HIGH scenario.

The difference between the product value of a biobased chemical and its petrochemical counterpart range from about −3600 ϵ>/t to 2500 ϵ/t. (The negative difference of values

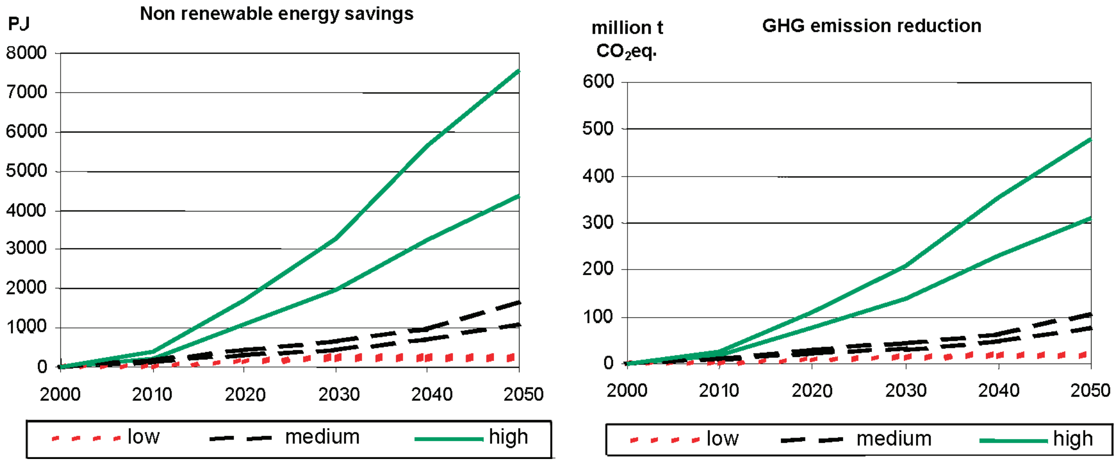

FIGURE 2. Nonrenewable energy savings and GHG emission reduction (cradle-to-grave, incineration without energy recovery) in the three scenarios for lignocellulose and starch as a feedstock. The lower curves for each scenario refer to the production of biobased chemicals from starch, while the higher curves represent the production from lignocellulose.

indicates that the biobased chemical has higher product value than its petrochemical counterpart. In this case the biobased chemical is not competitive.) For succinic acid, adipic acid, acetic acid and *n*-butanol, this difference is highly dependent upon technology developments. For PHA and ethylene, this difference is also strongly influenced by the scenario considered. Finally, PTT, PLA, and ethyl lactate show a rather robust difference in product values.

As explained in the methodology, the market projections account for the time needed for technology diffusion of biobased chemical production capacity. Comparing the market potentials (which include the delay for diffusion) and the economic potentials (which do not account for the delay) we find that the delay for the adaptation of biobased chemical production is significant. In the first decades, the economic potentials are only realized to a limited extent, for example, 51% in the LOW scenario, 83% in the MEDIUM scenario, and 53% in the HIGH scenario in 2020. In the past decade, the market potentials are, in general, rather close to the economic potentials (mostly between 90 and 100%), with the MEDIUM scenario being an exception with a share of 46%. This is due to the fact that biobased ethylene becomes economically viable at the end of the scenario, but only a small part of the potential is already implemented due to the delay from technology diffusion because the product value of biobased ethylene is higher than the depreciated production costs of petrochemical ethylene.

Economic and Environmental Benefits. By deducting the total of all product values of biobased chemicals (according to the market potential) from the total of all product values of their reference petrochemicals, the achievable savings for the economy can be estimated. As discussed earlier, some biobased chemicals have a green premium. As a consequence, the total difference of product values can be negative, representing a net loss. This is the case in the LOW scenario between 2030 and 2050 and in the first decade for the MEDIUM scenario. In 2050 the total savings of product values savings are −0.13, 6.7, and 74.8 billion € in the three scenarios.

The total nonrenewable energy use (NREU) savings and GHG emission reductions have been calculated based on data for specific chemicals as presented in (*2*) NREU savings and GHG emission reductions that can be achieved by the production of biobased chemicals depend on the type of feedstock used; see Figure 2. In general, NREU savings and GHG emission reductions are higher if fermentable sugars from lignocellulose, instead of fermentable sugars from starch, are used; see also ref *2*. In all scenarios, the production of biobased chemicals leads to NREU savings as well as to GHG emission reductions.

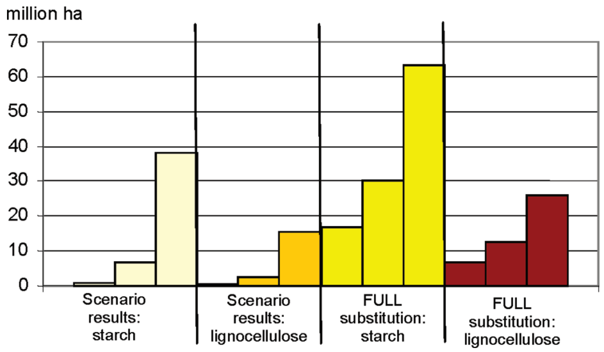

FIGURE 3. Total land used by 2050 for the selected organic chemicals according to the three scenarios (LOW, MEDIUM, and HIGH) and for full substitution of selected chemicals, i.e., 100% biobased chemical production.

Land use of the scenarios has been calculated based on specific land uses of chemicals as presented in ref *12*. Basis assumption of land use is that fermentable sugar yields are about 0.13 ha/t for sugars from starch and lignocellulosics. Land use remains relatively low in most scenarios according to our calculations; see Figure 3. The production of the biobased chemicals from fermentable sugar made of starch requires 1.0−38.2 million ha of land in 2050, whereas the production from lignocellulose as a biofeedstock results in only 0.4−15.6 million ha of land required. If we now assume that the selected organic chemicals are fully substituted by white biotechnology chemicals, then the land requirements in 2050 in the three scenarios range between 17 and 63 million ha for starch and between 7 and 26 million ha for lignocellulose. As a last step we make the hypothetical assumption that all organic chemicals—i.e., not only the selected ones—are covered at 100% by white biobased chemicals. Under these circumstances, the land requirements would be about twice as high, that is, reaching up to 126 million ha for starch and up to 52 million ha for lignocellulosics in 2050 (not shown in Figure 3).

Discussion

Uncertainty and Sensitivity. It should be kept in mind that the presented scenario results are not predictions of the future as (1) market potentials are based on parameters that are difficult to predict, for example, fossil fuel prices, and (2) the combination of parameters in the scenario, for example, a high demand of chemicals combined with low sugar price in Europe, does not necessarily reflect any linkages. Petrochemical feedstock prices, as well as fermentable sugar prices, are decisive for the market potentials of biobased chemicals. Other key parameters influencing market potentials are the development of the chemical sector and future technological developments.

Many parameters, however, had to be estimated by expert opinion, for example, future growth of the chemical industry, substitution rates of biobased chemicals, green premiums, and mechanisms and time scales of technology diffusion, and are thus uncertain.

Future fossil fuel prices depend on (global) political developments, developments of reserves, exploitation of different fossil resources, and demand. In the HIGH scenario fossil fuel prices rise up to 80 US$/barrel, but assuming fossil fuel prices of 105 US$/barrel would lead to only slightly higher shares of biobased bulk chemicals in 2050, that is, 83.5% instead of 83%.

Future sugar prices depend among others on trade policies, industrialization, and overall demand for nonfood biomass products. The fact that the development of fermentable sugar prices is unclear for the next 50 years leads to substantial uncertainties for the final results of this study. For example, assuming a high sugar price of 400 €/t in the HIGH scenario reduces the market potentials in 2050 from 113 to 37 million tonnes, and assuming a low sugar price of 70 €/t in the LOW scenario increases the market potentials from 5 to 8 million tonnes.

Future total production of chemicals depends on economic growth, industry structure, and on the global competitiveness of the European chemical industry. This competitiveness, in turn, may depend on the realization of white biotechnology and on the development of sugar prices in Europe as compared to sugar prices in other regions of the world, especially in Brazil. In the three scenarios, we have assumed a very wide range for (physical) growth reaching from 0 to 3% p.a., which would cover the entire range of more- or less-likely developments.

White biotechnology might be stimulated by policy measures, for example, subsidies. Only in the HIGH scenario have moderate subsidies—i.e., 1–5% of the product value of the biobased chemicals—been taken into account. Without these subsidies, however, the market potential in the HIGH scenario only decreases by 0.1%. On the other hand, assuming a direct subsidy of 10% of the product value in the LOW scenario leads to a 25% increase of the market potential in 2050 in the HIGH scenario.

To summarize, high market potentials of biobased chemicals in Europe are possible only if technological developments in biotechnological processes proceed, if biofeedstock costs are lower than current sugar prices, and if fossil fuel prices increase. Supportive measures to shorten the adoption process would also be desirable in a European policy to stimulate the introduction of biobased chemicals.

Putting the Benefits into Perspective. By 2050, the total product value of biobased chemicals amounts to 6−103 billion € in the various scenarios, and in 2004 the total sales of bulk chemicals in Europe were 240 billion € (*23*). The HIGH scenario, especially, offers considerable product value savings (74.8 billion €), whereas economic benefits in the MEDIUM scenario (6.7 billion €) are considerably lower. The LOW scenario entails minor additional expenses compared to the petrochemical benchmark.

For the annual added value of the biobased chemicals, we calculated about 1.8, 8.8, and 33.2 billion € in the three scenarios in 2050. For comparison, Mc Kinsey estimates an added value of about 11−22 billion € by 2010 for the total of white and red biotechnology (biotechnology for medical processes) also including fine chemicals, pharmaceuticals, and enzymatically produced chemicals that have a much larger economic potential compared to fermentation-based bulk chemicals, especially on the short-term (*1*). For comparison, our results range between 0 and 2.5 billion € added value in 2010.

Covering all results, we found NREU saving potentials between 7 and 67% compared to the NREU of the fossil production of the selected reference chemicals. Compared to the NREU of petrochemical production of all organic chemicals, White biotechnology allows saving 3–5% energy in the LOW scenario, 9–14% in the MEDIUM scenario, and 18–32% in the HIGH scenario. Under the assumption that the importance of energy use in the chemical sector will not change decisively in the decades to come, we estimate that white biotechnology chemicals allow savings of 0.3−3.0% of the NREU of the entire economy in 2050; the range covers all three scenarios for starch and for lignocellulosics. The saving percentages for GHG emissions are in a similar range. Thus, the savings for NREU and GHG emissions are limited if the comparison is made at a total economy's scale, because the chemical sector represents only roughly 10% of the total energy use in the EU. At the level of the chemical industry, however, these savings can be substantial, especially if one considers that they are achieved among white biotechnology chemicals representing not more than 38% of all organic chemicals. These energy savings and GHG emission reductions by white biotechnology for bulk chemical production may become increasingly important as the improvement potentials in conventional processes are more and more exploited.

The agricultural area in the EU-25 was about 179 million ha in 2002 (*26*), and it is estimated that by 2010 15% of arable farmland in the EU-15, and later in the 21st century, even more than 50 million ha can possibly be set aside and are not needed for food production (*27*). Assuming the same percentages for the EU-25, about 27 million ha can be set-aside in 2010 and 77 million ha later in the 21st century. The land requirements for the production of the selected chemicals according to the scenario analyses are clearly lower: In the most land-intensive case (starch, scenario HIGH) a maximum of 1.8 and 38.2 million ha is used in 2010 and 2050, respectively. In contrast, the extreme case of production of all organic chemicals by white biotechnology in the HIGH scenario is not feasible if starch is used as feedstock because 126 million ha would be required in 2050. Moreover, about two-thirds or 52 million ha in 2050 of the set-aside land would be needed in the case lignocellulose is used as feedstock. Thus, land use is found to be no bottleneck for Europe (EU-25) for a pathway between the MEDIUM and the HIGH scenario, especially if the use of lignocellulosic feedstock is successfully developed. However, an in-depth analysis of the land use competition between bioenergy and chemicals would be required in order to evaluate the upper limit for the production of biobased bulk chemicals. It is expected that the production of the selected chemicals is, in general, feasible from a land availability point of view but that the production from starch in the scenario HIGH from 2040 onward could face some limitations. Therefore, in terms of not only energy use and GHG emissions but also land use and feedstock availability, the use of lignocellulosics as basis for fermentable sugar is highly recommended.

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Supporting Information Available

In the suppoting information (SI) more detailed information on the methodology and data used are available, and discussion of results is continued. This material is available free of charge via the Internet at http://pubs.acs.org.

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