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Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe

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Preface

This report summarises the findings of a study carried out on behalf of the European Commission's Joint Research Centre, Institute for Prospective Technological Studies (JRC/IPTS) by a research team from Fraunhofer Institute for Systems and Innovation Research FhG-ISI (Germany) and Utrecht Univerity (The Netherlands).

The overall aim of the study was to investigate the technical, economic and environmental potential of bio-based polymers in comparison with petrochemical plastics. The objectives and methodology of the study had been defined by JRC/IPTS with the aim to feed the results into Thematic Strategy on the Sustainable Use of Natural Resources and the Environmental Technology Action Plan, ETAP. The management and supervision of the research activities, as well as the analysis of the findings and the editing of the final report were carried out by JRC/IPTS.

The JRC/IPTS would like to thank Mr.U. Stottmeister from the Umweltforschungszentrum Leipzig, Germany, and Mr. R. Anex from the Iowa State University, United States, for their careful review and valuable comments to the study. We thank Ms. Arancha Pera Gilaberte for her contributions to the environmental analyses. We are also very grateful to Mr. Ludo R. Andringa for permitting the chapter "U.S. technology policy on biobased products"to be reprinted as Appendix 5 of this report.

The JRC/IPTS would also like to thank the external experts that attended the validation workshop in Brussels: E. Seewald (Bayer, Germany), W. Vorwerg (Fraunhofer Institut für angewandte Polymerforschung, Germany), B. Kerckow (Fachagentur Nachwachsende Rohstoffe, Germany), F. Marechal (APME, Belgium), J.G. Baudoin (Valbiom-FusagX, Belgium), C. Rupp-Dahlem (Roquette, France), W. de Wolf (DuPont, Belgium), D. Wittmeyer (ERRMA, Germany), J. Reske (INTERSEROH, Germany), R. Jongboom (Rodenburg Biopolymers, The Netherlands), J. Harings (Rodenburg Biopolymers, The Netherlands), F. degli Innocanti (Novamont, Italy).

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Preliminary Remark

Bio-based polymers are in their infancy. There are success stories and very promising developments but failures and serious problems also exist. This report attempts to give the full picture and to draw fair conclusions.

Given the still early stage of development of bio-based polymers the information basis used in this report may be less complete than for analyses on mature materials (here: conventional polymers). The quality of the information used and presented differs by chapter:

- Most of the information given in Chapter 2 can be considered as solid. This applies not only to the description of the production process and the material properties but by and large also to the environmental impacts (by polymer). To a lesser extent, it applies to the expected developments in cost structure and selling price. The estimation of *maximum* technical substitution potential at the end of the chapter should be considered as indicative only.
- The projections for future prices and production volumes of bio-based polymers, which are presented in Chapter 3, are subject to large uncertainty. To account for this difficulty, various scenarios are distinguished.
- The assessment of the environmental impacts at the EU level, as reported in Chapter 4, is based on assumptions about the implementation of advanced technology (with lower environmental impact) and on the projections discussed in Chapter 3. At this early stage of development of bio-based polymers, many impacts which are likely to be significant cannot yet be assessed; other impact categories will only be identified as the transition from petroleum-based polymers to bio-based polymers progresses. The choice of reference product (1 tonne bulk polymer) and simplifying assumptions made in relation to the system boundaries do not allow for taking into account all end products; nor all combinations of factors including locality, time, modes of transportation used and waste treatment technologies employed. The individual results of Chapter 4 are thus subject to large uncertainties. However, this uncertainty is inevitable since it is not feasible to account for all possible combinations of materials, end products and waste management, which, *ideally*, would need to be weighted with their respective *future* penetration rates.

In Chapter 5 and 6, the authors attempt to summarise the results, to present a balanced discussion and to draw sound conclusions for the key decision makers, i.e. for policy makers and for companies. Before making use of any results in this report the reader should, however, be aware of the underlying limitations intrinsic in both the techno-economic and the environmental assessment – and especially concerning the projections. In particular, the reader is advised to read the methodology and notes (Chapter 2, subsections 'environmental impacts'; Sections 3.4 and 4.1 to 4.4) in addition to the concluding chapters 5 and 6. This report is based on information on commercialised and emerging bio-based polymers. Other bio-based polymers which are currently in an earlier phase of R&D are *not* taken into account even though some of them might be produced on a respectable scale towards the end of the projection period of this report (year 2020). Bio-based chemicals that are not used for polymer production (e.g. solvents, lubricants and surfactants and other intermediates and final products) are outside the scope of this report; if they develop favourably, this could reinforce also the growth of bio-based polymers.

One of the well known enterprises in the area of bio-based polymers is the production of PLA by Cargill Dow, a joint venture of the agricultural company Cargill and the chemical company Dow. Recently Dow announced to pull out of this joint venture in order to concentrate on a product portfolio with a shorter business life cycle. However, since at the time of writing this report the joint venture still was intact, it is referred to throughout the text as Cargill Dow.

Executive summary

For several decades, plastics derived from fossil fuels have grown at a faster rate than any other group of bulk materials, and expectations are that this high growth trend will continue until 2020. This study analyses the question if bio-based plastics, being derived from renewable resources, could serve to offset to a certain extent the non-renewable energy use and greenhouse gas emissions of the EU plastics industry, as well as having other advantageous socio-economic effects such as diversifying agricultural land use.

An overview of the types of bio-based polymers, their producers (including their location), the production processes applied and the types of uses shows that bio-based polymers is an emerging field which is characterised by new synergies and collaborations between a broad variety of actors of the chemical, biotechnology, agriculture and consumer goods sector.

In order to obtain a better understanding of the importance of this emerging sector estimates have been made firstly for the technical substitution potential and then for more realistic production scenarios which implicitly take into account price differentials and other influencing factors. The total technical substitution potential, which can be derived from the material property set of each bio-based polymer and its petrochemical-based equivalent is estimated at 15.4 million tonnes for EU-15, or 33% of the total current polymer production. A more detailed analysis taking into account economic, social, ecological and technological influencing factors relating to the bio-based polymer value chain leads to the identification of three scenarios: WITHOUT P&M (policies and measures), WITH P&M and HIGH GROWTH. In absolute terms, bio-based polymers are projected to reach a maximum of 1 million tonnes by 2010 in the scenario WITHOUT P&M and max. 1.75-3.0 million tonnes by 2020 in the scenarios WITH P&M and HIGH GROWTH respectively. These (physical) amounts are equivalent to an estimated maximum (monetary) production volume of roughly 1-2 billion EUR by 2010 (scenarios WITH P&M and HIGH GROWTH) and 3-6 billion EUR by 2020 (scenario HIGH GROWTH).

While these are sizable quantities, they are modest compared to the expected production increase of petrochemical polymers by 12.5 million tonnes by 2010 and 25 million tonnes by 2020. Thus, the market share of bio-based polymers will remain very small, in the order of 1-2% by 2010 and 1-4% by 2020. This means that bio-based polymers will not provide a major challenge, nor present a major threat, to conventional petrochemical polymers.

Energy and GHG emission savings from bio-based polymers in specific terms were found to be 20-50 GJ/t polymer and 1.0-4.0 t CO_{2eq}/t polymer respectively (Chapter 4.2.1). Bio-based polymers are thus very attractive in terms of specific energy and emissions savings. In absolute terms, savings are rather small: as a proportion of the total EU chemical industry, energy savings amount to 0.5-1.0% by 2010, up to a maximum of 2.1% by 2020; compared to the total EU economy the figures are 0.1% until 2010 and 0.2% until 2020 (Chapter 4.3.1). Greenhouse gas emissions savings amount to 1-2% by 2010, up to a maximum of 5% by 2020; compared to the total EU economy the figures are 0.1% until 2010 and 0.2% until 2020. Bio-based polymers therefore cannot offset the additional environmental burden due to the growth of petrochemical polymers (there is a gap of a factor of about 20 to 40). It is also out of the question that, within the next two decades, bio-based polymers will be able to meaningfully compensate for the environmental impacts of the economy as a whole. However, it is not unthinkable that the boundary conditions for bio-based polymers and the energy system will change dramatically in the decades after 2020, e.g. due to substantially higher oil prices. If, *ceteris paribus*, bio-based polymers would ultimately grow ten times beyond the HIGH GROWTH projection for 2020 (i.e., to about 30 million tonnes), this could avoid half of the chemical sector's current GHG emissions, without accounting for major technological progress (efficiencies, yields) in the decades after 2020. These considerations for the very long term do not justify any concrete (policy) action today, they are rather intended to demonstrate the implications of the comparatively low production volumes until 2020 (compare also per capita values in Table 3-7).

The results of the calculations on land use requirements (Chapter 4.3.1) show that by 2010 a maximum of 125,000 ha may be used for bio-based polymers in Europe and by 2020 an absolute maximum of 975,000 ha (High Growth Scenario). Comparing this with total land use in EU15 for various purposes shows that, if all bio-based polymers were to be produced from wheat, land requirements as a percentage of total land used to grow wheat range from 1% WITH P&M to 5% in the case of HIGH GROWTH. As a proportion of total cereals these figures are a factor 2 lower. Compared to total set-aside land (1997 values), the percentage of land required ranges from 3.6% to 15.4%; as a percentage of industrial crops the range is similar. Bio-based polymers are thus seen to have modest land requirements and will not cause any strain within the EU on agricultural land requirements in the near future. As a consequence the employment potential in the agricultural sector is also very limited until 2020.

Summarising the potential environmental and socio-economic effects it may be concluded that while environmental effects in specific terms are high, effects in absolute terms relative to those of total industry or society are low. Job creation potential is also low. It must be emphasized that these relatively low contributions have their reason in the comparatively low production volumes of bio-based polymers until 2020. Even so, the societal ramifications may be significant and positive in the "green chemistry" arena, for education, for the image of the companies involved (including producers and users of bio-based polymers) and ultimately also for the innovation climate.

The interviews and workshop held within the scope of this project also showed that it is not sufficient simply to lower the cost of bio-based polymers production and facilitate their market introduction. It is equally important to accompany this with R&D activities in the field of polymer processing: Processors also must have access to the relevant additives which should be biodegradable, in order for the biopolymer to be fully biodegradable (examples given: dyes, anti-static additives).

The production of biobased polymers is an emerging sector of industrial biotechnology, both in terms of public and private R&D as in first product niche markets such as e.g. packaging or car-interior fittings. The environmental impacts of biobased polymers in terms of energy and GHG emission savings compares favourably to petrolbased polymers. Targeted policy measures could have a stimulating impact similar to those already in place to support the uptake of renewables in energy production.

However, the implementation of such measures can be difficult. If for instance tradable certificates are discussed, the complexity of the chemical processes and products in question requires a sophisticated monitoring and verification system. The associated costs could easily outweigh the achieved environmental benefits. These problems could be avoided through simpler generic measures such as VAT reduction, focused publicly R&D funding, standardisation of products and processes, and campaigns aiming at raising public awareness. More difficult to implement and to assess with regards to its efficiency is the support of the production of biobased polymers through integration into existing policy schemes, such as the common agricultural policy, the climate change policy and waste resp. waste management related legislation.

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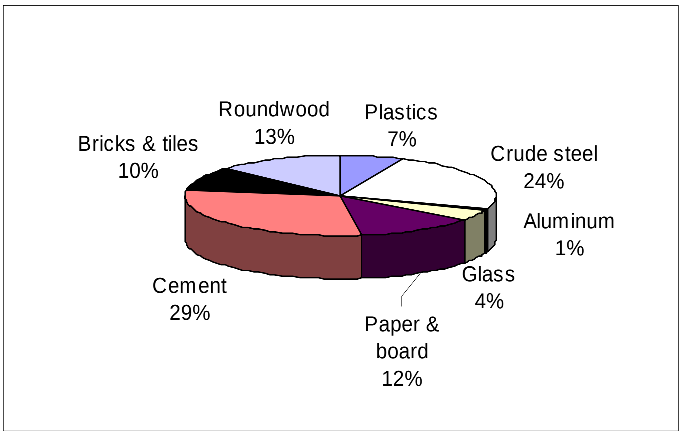
1. Introduction

1.1 Materials, plastics and policy

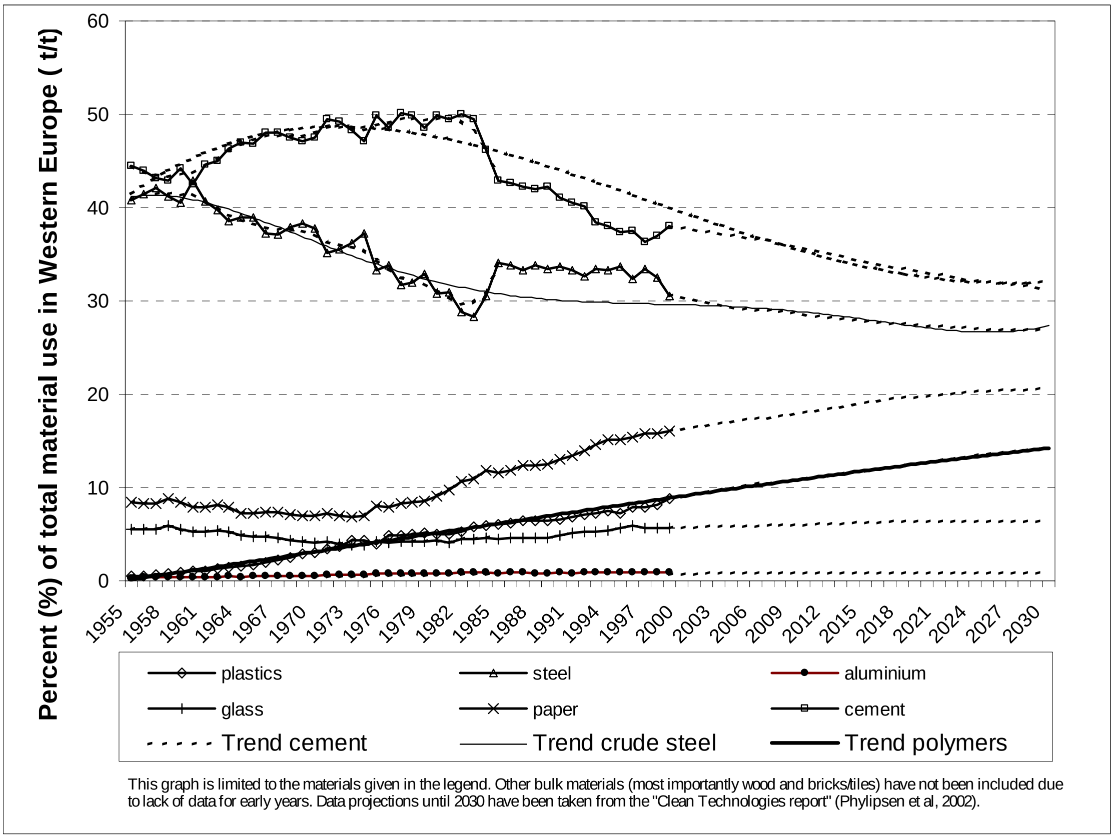
Polymers are the newcomers among the bulk materials used in modern economies. They have been used in substantial quantities for only five to seven decades. In contrast, wood and clay have been used since the existence of mankind, glass for 5500 years, steel for 3500 years, paper for 1900 years, cement for 180 years and pure aluminium for 120 years. In high-income countries, polymers have overtaken aluminium and glass in terms of quantities used (mass) and now account for roughly 10% of the total amount of bulk materials (see Figure 1-1).

Figure 1-1: Production of bulk materials in Western Europe, mid/end 1990s



The fact that plastics are in a comparatively early stage of their product life cycle explains the particularly high growth rates of plastics production worldwide. For example, plastics production in the EU grew by 4.4% p.a. between 1985 and 2000, while the total production of all bulk materials (without roundwood and bricks/tiles) increased merely by 1.4% p.a. (compare Figure 1-2). High growth is also projected for the future: According to the IPTS study “Clean technologies in the material sector”, plastics represent the fastest growing group of bulk materials, with growth rates outpacing GDP until 2020 and slightly lower rates in the period 2020-2030 (Phylipsen et al., 2002). In the next three decades plastics are expected to gain important segments of the glass market and to substitute, to a lesser extent, steel (Phylipsen et al., 2002).

Figure 1-2: Bell-shaped curves representing the shares of bulk materials used in the EU



This graph is limited to the materials given in the legend. Other bulk materials (most importantly wood and bricks/tiles) have not been included due to lack of data for early years. Data projections until 2030 have been taken from the "Clean Technologies report" (Phylipsen et al, 2002).

The same study comes to the conclusion that the environmental impacts of current plastics are rather high compared to other materials. This concerns both a comparison in specific terms (per tonne of material) and in absolute terms for the EU. The study results are based on the Ecoindicator '99 method (Pré Consultants, 2000) which incorporates the environmental impact categories climate change, summer smog, winter smog, carcinogenics, acidification/eutrophication, ozone depletion, radiation, ecotoxicity, land use, minerals depletion and fossil fuel depletion (Phylipsen et al., 2002). These results indicate that a business-as-usual development in the plastics sector may be in conflict with the pursuit of sustainable production and consumption. It is a limitation of the study by Phylipsen et al. (2002) that it does not account in quantiative terms for the differences in functionality across the materials; for example the amount of polymers needed for a given packaging task may be lower for polymers than for paper which may lead to an overall environmental advantage for polymers.[1] On the other hand, the fact that the polymer industry as a whole and the production of the largest polymer groups leads to rather high environmental impacts in absolute terms (also compared to other materials) justifies an analysis of options to reduce these adverse side effects. This approach is in line with the goals formulated in the **6th Environmental Action Programme of the European Commission**, which emphasizes the need to fight climate change, to protect the environment and human health in general, and to promote the further "greening" of products and processes.

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[1] It should be kept in mind here that it is practically impossible to account for all differences in functionality in all applications.

Another important cornerstone was the EU Report "Environmental Technology for Sustainable Development" from the Commission to the European Council of Barcelona which led to the decision that the Commission will develop an Action Plan for promoting clean technologies, as announced in the Synthesis Report to the European Council. A part of this plan is the use of clean technologies in the bulk material sector. Given the importance of plastics among the bulk materials it is not surprising that plastics are among the materials that are studied in more detail. This report entitled "Techno-economic feasibility of large-scale production of bio-based polymers in Europe (PRO-BIP)" is hence the summary of research carried out to support the Institute of Prospective Technological Studies (IPTS) in developing this **Action Plan**.

There are several **options to reduce the environmental impacts related to polymer** production and use, many of which are also relevant for other bulk materials. Important strategies are

- increased energy efficiency and material efficiency (yields) in all processes in the production chain leading to polymers,
- increased end-use material efficiency, i.e., ensuring the same product service by lower amounts of material (e.g. by use of thinner plastic films),
- improved waste management by recycling of materials, re-use of product components, energy recovery in waste-to-energy facilities (incineration) and - in the case of biodegradable polymers – digestion (with energy recovery) and composting,
- **replacement of petrochemical feedstocks by bio-based feedstocks.**

This study focuses on the latter option which, in principle, offers wide scope for change since bio-based polymers now account for **less than 0.1%** of the total production of polymers in the EU (ECCP, 2001). Bio-based polymers have been attracting more and more attention in the last few years. While, for example, EU policy on renewable resources was until recently typically limited to energy supply issues, the use of renewable raw materials for the production of bio-based materials was taken into account by the **European Climate Change Programme** (ECCP, 2001). The goal of the ECCP, which ran from mid-2000 to mid-2001 was to help identify the most cost-effective and environmentally beneficial measures enabling the EU to meet its target under the Kyoto Protocol (UNFCCC, 1997). Bio-based materials – including bio-based polymers, lubricants, solvents and surfactants – were found to be an interesting option, albeit with limited emission reduction potentials for the short term (until 2010). It was also found that bio-based materials offer clearly higher emission reduction potentials in the longer term, especially by application of novel technologies.

1.2 Looking back

The first man-made polymers were derived from biomass resources (animal bones, horns and hooves, often modified; *celluloid*; casein plastics, *shellac*; Stevens, 2002). However, they were more and more displaced by petrochemical polymers parallel to the growth of the petrochemical industry since the 1930s. While the oil price shocks of the 1970s led to renewed interest in the possibilities offered by non-petrochemical feedstocks, this did little more than temporarily slow the pace of growth in petrochemical polymers. Since the 1980s and especially in the 1990s, however, a **comeback of bio-based polymers** is observable in certain application areas. One of the main drivers for this development in the last two decades was the goal to provide the market with polymers that are biodegradable. In principle, biodegradable polymers can also be manufactured entirely from petrochemical raw materials. But bio-based polymers, defined here as polymers that are fully or partially produced from renewable raw materials, have so far played a more important role in the domain of biodegradable polymers. These developments have also been a stimulus for R&D on bio-based polymers which are *not* biodegradable.

In Europe, **biodegradable polymers** were originally developed and introduced to the markets for two main reasons. Firstly, the limited volume of landfill capacity became more and more a threat and secondly, the bad general public image of plastics called for more environmentally friendly products. While the first issue has largely disappeared from the top of the public agenda due to the introduction of plastics recycling schemes and due to newly built incineration plants, the **environmental performance** is an important argument for bio-based polymers, including their biodegradable representatives. Apart from consumer demand for environmentally friendly polymers ("market-pull"), **technological progress** ("technology push") represents a more and more important driver.

For many decades, **cellulose polymers** played a key role in a wide range of applications, for example apparel, food (e.g. for sausages) and non-plastics (e.g. varnishes). In the meantime, these bio-based polymers have lost important markets mainly to polyolefins. On the other hand, attempts are being made to develop new cellulose polymer markets in the areas of films, fibres, non-plastics and for natural fibre composites (N.N., 2002).

Since the 1980s, more and more types of **starch polymers** have been introduced. To date, starch polymers are one of the most important groups of commercially available bio-based materials. At the outset, simple products such as pure thermoplastic starch and starch/polyolefin blends were introduced. Due to the incomplete biodegradability of starch/polyolefin blends these products had a negative impact on the public attitude towards biodegradable polymers and they damaged the image of the companies involved. It took many years to repair this damage, which was achieved largely by introduction of more advanced copolymers consisting of thermoplastic starch and biodegradable petrochemical copolymers.

Widespread R&D activities were conducted to develop cheaper and simpler ways of producing **polyhydroxyalkanoates (PHA)**, reaching from production by fermentation to direct synthesis in crops. While considerable progress was undoubtedly made, Monsanto terminated their activities in this area in 1999 since the envisioned PHA yields for the production in crops (e.g. maize) were not reached. Being one of the most important players in the field at that time, Monsanto's retreat revived **principal doubts** about the feasibility and the sensibleness of commercializing large-volume bio-based polymers (e.g. Gerngross and Slater, 2000). Nevertheless R&D has continued in public and private organisations.

In the meantime major progress has been made in industrial production of other types of bio-based polymers. Most importantly, Cargill Dow, a joint venture of Cargill and Dow started up a plant in Nebraska in 2001 for the manufacture of **polylactic acid (PLA)** with a total capacity of 140 kt per year (At the time of publishing this report, Dow announced to pull out of this venture due to a strategic shift in their product portfolio). Apart from being the monomer for PLA, lactic acid has also the potential to become a new (bio-based) bulk chemical from which a variety of other chemicals and polymers can be produced (acrylic acid, propylene glycol, propylene oxide and others).

1.3 Looking ahead

Commercialisation is underway in several other cases. Among the important industrial players are DuPont, Metabolix, Novamont and Proctor & Gamble. Important milestones expected for the short to medium term are the large-scale production of bio-based **polytrimethylene terephthalate (PTT)** by DuPont and Proctor & Gamble’s initiative in **polyhydroxyalkanoates (PHA)** - a product family, which many experts in the field had already given up with regard to industrial production. In both cases the production is based on biotechnology (as also for PLA) which is a key driver for the development and commercialization of large-scale bio-based processes (“technology-push”). This is in line with the high expectations linked to biotechnology with regard to its potential contribution to building a **sustainable bio-based economy** which combines eco-efficient bio-processes with renewable bio-resources (OECD, 2002; COM (2002) 27 final, 2002). Another technological driver is the progress in nanotechnology which also offers new possibilities for bio-based polymers.

Regarding the supply of bio-based resources, the possibility of providing **domestic agriculture** with a new source of income could turn out to be an important driver for the production and use of bio-based materials. Additional impetus could come from the **New Member States and Associated States** of the European Union with their vast agricultural and silvicultural areas and large potential for improvement in agricultural practice. Last but not least, **energy and environmental policy** (including climate policy) could substantially influence the future development of bio-based polymers.

To summarise, bio-based polymers might offer a way forward in **satisfying future material demand while at the same time reducing corresponding negative environmental impacts and providing income to the agricultural sector**. An additional important impact associated with bio-based polymers is a reduction in economic risk/uncertainty associated with reliance on petroleum imported from unstable regions.

In addition to the examples given above there are **numerous other developments in the chemical industry aimed at bringing bio-based polymers to the market**. Several large chemical companies are making considerable efforts to develop, test and launch bio-based polymers which are targeted not only for niches but also for bulk applications (see, for example, the website of the BREW project; BREW, 2003). Important activities are also being undertaken by small and medium-sized enterprises (SME) active in polymer production and processing. There are several examples of commercialised and prototype products made from bio-based products giving an indication of the wide range of possibilities and activities in this field (see Section 2.8.3). As this report will show in more detail, there are good reasons to assume that bio-based polymers represent an **emerging group of materials**. This raises numerous technical, environmental, economic and political questions.

1.4 Objectives and scope

This study investigates the technical, economic and environmental potential of bio-based polymers in comparison with petrochemical plastics. The ultimate **objective** is to develop **projections for bio-based polymers in Europe** and to discuss them in terms of market boundary conditions and environmental impacts.

In the first instance, the **geographical scope** of the study is the EU 25. In cases where promising technologies or products developed in the U.S., Japan or elsewhere serve to illustrate further opportunities for the EU, these are also taken into account. In addition, a global viewpoint will be taken in addition to the EU perspective in order to obtain a feeling for the dynamics of the sector as a whole.

The **time horizon** of this prospective study is the year **2020**[2]. The **base years** chosen for the analysis are **2000, 2010 and 2020**. Relevant **historical** developments are studied both for bio-based and for petrochemical polymers.

With regard to the **type of products and their production** the scope of this study can be described as follows:

- The focus is on **bio-based polymers** and *not* on biodegradable polymers. Bio-based polymers *can* be, but are not necessarily, biodegradable. For example, starch polymers are generally biodegradable while crystalline PLA is virtually nonbiodegradable. Moreover, several petrochemical (co-)polymers exist that are biodegradable. Biodegradability is therefore not a selection criterion for inclusion in this study.

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[2] According to original plans the time horizon for this study was the year 2030. However, in the course of work the conclusion was drawn that such a long time period would lead to too speculative statements. The temporal scope was therefore restricted to the period 2000-2020.

- Neither is the **share of biogenic carbon** in the product a selection criterion: As a consequence, both polymers with a *high* share of embodied biogenous carbon (max. 100%) and polymers with a *low* share are taken into account. The rationale behind this decision is that high shares of embodied biogenous carbon may lead to relatively high polymer prices which limit their market volume and the attendant environmental benefits. In contrast, allowing polymers with a lower content of renewable carbon to enter the market without restriction could lead to more cost-effective solutions (greater environmental benefits at lower cost).
- When biodegradable polymers were introduced in the 1980s, **blends of starch with non-degradable petrochemical polymers** were also introduced to the market. Since this type of product is only partially biodegradable, it led to complaints from the environmental community and subsequently to a poor public image. As a consequence these products now play a subordinate role (in the EU). They are therefore excluded from this study.
- **Cellulosic polymers** have been on the market for decades but – as a whole – they are losing market share to petrochemical polymers. Cellulosic polymers are therefore discussed rather briefly.
- **Natural fibres and composites of natural fibres with petrochemical polymers** are not studied in this report since they are generally not included when reference is made to bio-based polymers. It should, however, be noted that the industrial use of natural fibres is growing and that first analyses show low environmental impacts compared to their synthetic counterparts (Patel et al., 2003). This indicates also very interesting possibilities for combining natural fibres with bio-based polymers. While this group of composites is, in principle, within the scope of this study only very few commercialised examples are known (see also Section 2.8.3).
- **There are three principal ways to produce bio-based polymers,** i.e.
  i) to make use of natural polymers which may be modified but remain intact to a large extent (e.g. starch polymers),
  ii) to produce bio-based monomers by fermentation which are then polymerized (e.g. polylactic acid) and
  iii) to produce bio-based polymers directly in microorganisms or in genetically modified crops.
- While all three pathways have been taken into account in this study, the third pathway is currently only relevant for PHAs and although commercialisation efforts are underway, bulk volume applications appear to be still many years off. This study therefore focuses on the first two pathways of which the latter seems to be gaining importance.
- The key selection criterion for the bio-based polymers covered by this study is the **proximity to or the realization of commercialization**. This means that polymers and polymer precursors that have been discussed in literature as potential bulk products but for which there are no evident signs of “take-off” have not been included in this study (examples are levulinic acid and ethylene from bioethanol). For their inclusion a very detailed analysis would be required which is beyond the scope of this study.

- Depending on their materials properties, bio-based polymers can be used for **plastics products** (manufactured by extrusion, injection molding, blow molding, vacuum forming etc.) and for **non-plastics** such as varnishes, or lubricant additives. Since only little information is available on non-plastic polymer applications, this report focuses on bio-based polymers used as plastics.

The **environmental assessment** is based on information from the open literature with the consequence that the results might not be fully comparable across the products in terms of the methodology used. Moreover, information on environmental impacts is not or only partly available for some products covered by this study (PBT, PBS, PUR, PA). These problems could only be avoided by conducting original life-cycle assessments for all products, which is again beyond the scope of this study.

To summarise, the approach taken in this study obviously results in some **limitations** which need to be taken into account in the interpretation phase. However, the analyses presented in the following *do* allow us to generate a first estimate of economic and environmental potential of bio-based polymers in comparison with petrochemical plastics and to derive some conclusions for policy makers.

1.5 Structure of the report

Apart from the introductory chapter (Chapter 1) this report is divided into five chapters, with each chapter corresponding to a research task as identified in the project implementation plan.

The main purpose of **Chapter 2** is to provide an overview of the technologies for the production of seven major groups of bio-based polymers, of their properties, the technical substitution potential, the product prices and the environmental impacts. This has been achieved by conducting an in-depth literature survey (printed publications, internet) and by interviewing experts in the field.

The overall goal of **Chapter 3** is to develop projections for the production of bio-based polymers until 2020. As the first step, the influencing factors and boundary conditions for the future production and use of bio-based polymers are identified and discussed (Section 3.1). Since prices are key factors for future market development the purpose of the following sections (3.2 and 3.3) is to prepare projections for the prices of petrochemical and of bio-based polymers. In Section 3.2, regression analyses for three petrochemical bulk polymers are performed in order to distinguish the contribution of technological learning, the scale of production and the oil price on the historical development of polymer prices. This insight is firstly used to project future prices of petrochemical polymers for various scenarios (oil price, polymer production). Secondly, in Section 3.3, the relationships found are translated to bio-based polymers and the prices of these materials are projected. Using the results of Section 3.2 and 3.3, market projections for both groups of polymers are presented in Section 3.4. Various scenarios are distinguished, in order to reflect different trajectories for economic growth, fossil fuel prices, crop prices and policy conditions.

In **Chapter 4** the environmental effects related to the wider use of bio-based polymers are assessed for the projections developed in Chapter 3. Two aspects are studied. Firstly, the impacts on the use of fossil fuels on land use and on greenhouse gas emissions (GHG) are assessed; particular attention is paid to the enlargement of the European Union and the accompanying changes in the European agricultural sector. Secondly, the question of whether the avoidance of environmental impacts due to the introduction of bio-based polymers can compensate (or even over-compensate) for the additional environmental impacts caused by expected high growth of petrochemical plastics is analyzed.

Chapter 5 finally discusses the question to which extent the diffusion of bio-based polymer technologies in industry can be stimulated through policy measures at EU level. Suitable policy measures are discussed and their effects analysed.

2. Existing and emerging technologies for bio-based polymers in bulk chemical applications

This chapter discusses **seven emerging groups of bio-based polymers**. For each of these, an overview is given of current production technologies, of their properties, the technical substitution potential, the production cost and the environmental impacts. The order followed in this chapter roughly represents the current importance of each group of bio-based polymers in terms of production volumes in Europe (see Tables 2-1 and 2-2). Starch polymers and polylactic acid (PLA) are now clearly the most important types of polymers. Starch polymers have been the frontrunners in the bio-based polymer business, but could be surpassed in Europe rather soon (in terms of production). At the global level, PLA might be about to overtake starch polymers due to Cargill Dow's large-scale plant. Some of the other bio-based polymers that are not yet manufactured commercially are rather close to industrial production (PTT and PHA respectively). Other bio-based polymers listed in Table 2-1 are already produced commercially but they serve niche markets and therefore are produced only at very low levels (PUR; see also Table 2-2). The remaining polymers have been or are being discussed but it is often unclear how far from commercialization they might be; it should be noted that there may be further bio-based polymers belonging to these groups which, however, were deemed to be less important.

As shown in Table 2-1, the seven groups of bio-based polymers belong to four types of polymers, namely **polysaccharides, polyesters, polyurethanes and polyamides**.

- The **polysaccharides** covered generally represent modified natural polymers (see Table 2-1). Bacterial cellulose, which is a novel production process, is an exception since it is produced in a natural or genetically modified organism.
- In the case of the **polyesters**, the monomer (which may be an alcohol or an acid) is generally produced by fermentation from a renewable feedstock. The polyester may be composed of only one type of monomer. Wherever this is not the case, the copolymer is a petrochemical product for the products given in Table 2-1. Polyhydroxyalkanoates represent a special case since they can be either produced by fermentation or in a (genetically modified) crop, e.g. potatoes.
- In the case of **polyurethanes**, the polyols used are bio-based while the isocyanate component is synthesized by petrochemical processes.
- The three representatives of the fourth group, i.e. **polyamides**, are produced by fermentation or by conventional chemical transformation of a crop-derived feedstock (depending on the type).

Bio-based polymers that are **not covered in this study** are chitin (a polysaccharide; mainly produced from shellfish waste), proteins (such as collagen, casein and zein; the latter two are mainly used for non-plastic applications), amino acids (e.g. polyaspartic acid; mainly used for non-plastics) and natural fibres (Stevens, 2002; Hüsing et al., 2003). The potential volumes of these products are considered too small to be included in this study.

Table 2-1: Overview of currently most important groups and types of bio-based polymers

No.	Bio-based polymer (group)	Type of polymer	Structure/Production method
1.	Starch polymers	Polysaccharides	Modified natural polymer
2.	Polylactic acid (PLA)	Polyester	Bio-based monomer (lactic acid) by fermentation, followed by polymerisation
3.	Other polyesters from bio-based intermediates	Polyester	
a)	Polytrimethyleneterephthalate (PTT)		Bio-based 1,3-propanediol by fermentation plus petrochemical terephthalic acid (or DMT)
b)	Polybutyleneterephthalate (PBT*)*		Bio-based 1,4-butanediol by fermentation plus petrochemical terephthalic acid
c)	Polybutylene succinate (PBS)		Bio-based succinic acid by fermentation plus petrochemical terephthalic acid (or DMT)
4.	Polyhydroxyalkanoates (PHAs)	Polyester	Direct production of polymer by fermentation or in a crop (usually genetic engineering in both cases)
5.	Polyurethanes (PURs)	Polyurethanes	Bio-based polyol by fermentation or chemical purification plus petrochemical isocyanate
6.	Nylon	Polyamide	
a)	Nylon 6		Bio-based caprolactam by fermentation
b)	Nylon 66		Bio-based adipic acid by fermentation
c)	Nylon 69		Bio-based monomer obtained from a conventional chemical transformation from oleic acid via azelaic (di)acid;
7.	Cellulose polymers	Polysaccharides	a) Modified natural polymer b) Bacterial cellulose by fermentation

Table 2-2: Current and potential large volume producers of bio-based polymers

Producer	Region	Polymer type and trade name(s)	2002 Production (kt p.a.) **EU-15**	2003 Capacity (kt p.a.) **EU-15**	2010 Capacity (kt p.a.) **EU-15**	2002 Production (kt p.a.) **global**	2003 Capacity (kt p.a.) **global**	2010 Capacity (kt p.a.) **global**	2003 Price (/kg) **global**	2010 Price (/kg) **global**
Starch polymers[c]			30	62	(200-250)	30	(77-200)	(200-300)	(€3.00)[k]	
Novamont, Italy	EU	**Mater-Bi®**	25[3,e]	20[3]	>20	25[3,e]	35[3,f]	>20	€1.50-€4.50[3,h]	
Rodenburg, Netherlands	EU	**Solanyl®**	3 (0-7)[10,o]	40[10]	40	3 (0-7)[10,o]	40[10]	40	€1.00[10]	
National Starch and Chem., U.S.	US	**Ecofoam®**				(20)[9,g]	(20)	(>20)		
Chinese company	*Asia*	*Thermoplastic starch*					*(100)*[6,I]	*(100)*	*€0.60*[6]	
BIOP, Germany	EU	**BIOpar®**		(10 in 2004)[20]	150[20]		10 (~2004)[20]	150[20]		
Biotec, Germany	EU	**Bioplast® TPS**	2[6]	2[6]		2[6]	2[6]			
Japan Corn Starch, Japan	Asia	**Cornpol®**								
Nihon Shokuhin Kako, Japan	Asia	**Placorn®**								
Potatopak, Avebe, Earthshell		Baked starch derivatives								
Polylactic acid (PLA)				1	250-500	30	143.5	530-1150	(€3.00)	€1.50
Cargill Dow LLC, U.S.	US	**Natureworks®** (Mitsui **Lacea®** in Japan)			150-250[12]	30[24]	140[12]	280-500[12]	€2.20-€3.40[12,j]	€1.35[12]
Hycail, Netherlands	EU	**Hycail HM, Hycail LM**		1[13]	100-250[13]		1[13]	100-250[13]		€1.80[13]
Toyota, Japan	Asia	**(Toyota Eco-Plastic)**					50 (in 2004)[15]	150-400[12]		
Project in China	Asia	Conducted by **Snamprogetti**, Italy					2.5 (mid 2003)[16]			
Other potential BB-polyesters (currently petrochemical-based)								3-44	(€2.00-€5.00)	
In near future										
Dupont	US	Poly(trimethylene terephthalate) PTT Sorona™					10 (in 2004)[17,q]	(41)[17]	(€2.30)	
Mitsubishi Chemical, Japan	Asia	Poly(butylene succinate)					(3 by 2006)[22]	3	(€5.00[6])	
No clear time frame										
Showa HighPolymer, Japan	Asia	Poly(butylene succinate) **Bionolle 1000®** and Poly(butylene succinate adipate) **Bionolle 3000®**					(3, (6 in 2004)[22]		€3.50[6]	€3.00[6]
		Poly(butylene terephthalate) PBT							€2.17[7]	
Dupont, Japan	Asia	Poly(butylenesuccinate terephthalate) **Biomax®**				(1-5[6])	(90[6,m])		€2.00[l]	
Eastman, Japan	Asia	Poly(butylenesuccinate terephthalate) **EastarBio®**					(15[22])		(€2.00[l])	
BASF, Japan	Asia	Poly(butyleneadipate terephthalate) **Ecoflex®**					(8[22], 30 in 2004)		(€2.00[l])	
Polyhydroxyalkanoates PHAs)										
PHA homopolymers									€20.00[4]	(€2.00-€3.00)
Metabolix, U.S.	US	P(3HB), P(3HO)								€2.20[6]
Biomer, Germany	EU	P(3HB) **Biomer®**	(0.05)[p]	(0.05)[p]		(0.05)[p]	(0.05)[p]		€20.00[4]	€3.00-€5.00[4]
Mitsubishi Gas, Japan	Asia	P(3HB) **Biogreen®**								
PHA copolymers						0.05	1.4	30-60	€10.00-€12.00	€2.50-€3.00

Producer	Region	Polymer type and trade name(s)	2002 Production (kt p.a.) **EU-15**	2003 Capacity (kt p.a.) **EU-15**	2010 Capacity (kt p.a.) **EU-15**	2002 Production (kt p.a.) **global**	2003 Capacity (kt p.a.) **global**	2010 Capacity (kt p.a.) **global**	2003 Price (/kg) **global**	2010 Price (/kg) **global**
Metabolix, U.S.	US	P(3HB-*co*-3HV) **Biopol**®				(0.05)[p]	1.1[5,b]	not known	(€10.00-12.00)[14]	€3.00-€5.00[14]
P&G, U.S. (& Kaneka, Japan)	US/Asia	P(3HB-*co*-3HHx) **Nodax**®				0.0005[11]	0.25[11]	20-50[6]		€2.50[6]
PHB Industrial, Brazil	S.Am	P(3HB-*co*-3HV)[a]				0.05[8]	0.05[8]	10 (in 2006)[8]		
BB-polyurethanes (PUR)									(€2.30)	
Metzeler-Schaum, Germany	EU	PUR from bio-based polyol							(€2.27)[7,n]	
BB-polyamides (PA)									(€2.75)	
No commercialised products									(€2.74)[7,n]	
Cellulosic polymers										
Plant cellulose-based		*Tot vol (4000)[19,r], not included in summations*					(4000)[19,r]	(4000)[19,r]	(€3.30)	
Lenzing	EU	Regen cellulose **Lyocell®**							(€3.36)[7,n]	
Accordis	EU	Regen cellulose **Tencell®**							(€3.36)[7,n]	
Eastman	US	Cellulose acetate **Tenite®**							(€3.31)[7,n]	
IFA	EU	Cellulose acetate **Fasal®**							(€3.31)[7]	
Mazzucchelli	EU	Cellulose acetate **Bioceta®**							(€3.31)[7]	
UCB	EU	Cellulose acetate **Natureflex®**							(€3.31)[7]	
Bacterial cellulose									(€20)	
Weyerhauser, US	US	**Bacterial Cellulose** Cellulon®	negl.	negl.		negl.	negl.		(€20)[21]	
Ajinimoto, Japan	Asia	Bacterial Cellulose	negl.	negl.		negl.	negl.		(€20)[21]	
Mixed, other										
Borregard, Germany	EU	**Lignin-based** Lignopol®								
2B Biorefineries, Switzerland	EU	**Cellulose-based** 2B Gratec®								
Total bio-based polymers		(from this table) (other estimates/projections)	30	63	450-750 600[2]	60	222 226[2]	760-1560 500-1000[1]		
Total polymers			47,650[23]	(56,900)[23,d]	53,000[1]	187,000[18]	(230,000)[18,d]	(260,000)[23,24]		

Refs: [1]ECCP (2001); [2]Windels (2003).- IBAW data.; [3]Novamont (2003b); [4]Biomer (2003b); [5]Metabolix (2003); [6]Showa HP (2003), [7]PlasticsNews (2003); [8]PHB (2003); [9]Gross and Kalra (2002); [10]Rodenburg (2003); [11]P&G (2003); [12]Cargill Dow (2003); [13]Hycail (2003); [14]Petersen et al. (1999); [15]TMC (2003a); [16]ENI (2001); [17]Genencor (2003); [18]VKE (2003), [19]UNICI (2002); [20]BIOP (2003); [21]Weber (2000); [22]Nandini (2003); [23]APME (2003); [24]own est.

[a] Also producing some P(3HB).

[b] Based on 50,000L fermentor, batch time 40 h, yield (assumed) 100 g/L.

[c] Includes blends with biodegradable synthetics such as PCL, PVOH.

[d] Capacity 2003 = projected production 2003/(load factor 0.85)

[e] In-house production 2002 ~12 kt.p.a.; licensed production elsewhere (assumed outside EU) ~13 kt.p.a.

[f] Capacity 2003 ~20 kt.p.a.; licensed production elsewhere (assumed outside EU) ~15 kt.p.a.

[g] Not known if this figure is included in Novamont licensed production.

[h] Lower price foams, upper price films & specialty, average price (weighted) is estimated to be in the range of €2.50-€3.00.

[i] Estimate, could not be verified.

[j] Lower price for large volume sales, upper price for samples/small quantities.

[k] Novamont average (upper value of range) taken as rough estimate of category average.

[l] Based on CEH estimates.

[m] includes PET production; no separate figure available.

[n] Upper price in range "category II - annual volumes 2 to 5 million pounds".

[o] Exception: current production volume is an estimate since no figures have been released; real value lies between 0 and 7 kt.p.a., the latter being the capacity of the pilot plant.

[p] Assume typical scale-up is 20x pilot plant; take current production = est. pilot plant capacity

[q] Initial capacity 10.8 kt.p.a.; capability to expand to 45 kt.p.a.

[r] 1985 data – latest available.

2.1 Starch polymers

The frontrunners of the renaissance of bio-based polymers in the market today are those based on starch. A starch polymer is a thermoplastic material resulting from the processing of native starch by chemical, thermal and/or mechanical means. Starch polymers are biodegradable and incinerable and can be fabricated into finished products such as mulch film and loose fills through existing technology. Because of their relatively low cost, polymers based on starch are an attractive alternative to polymers based on petrochemicals. When starch is complexed with other co-polymers, the result can vary from a plastic as flexible as polyethylene to one as rigid as polystyrene.

Starch is the major storage carbohydrate (polysaccharide) in higher plants and is available in abundance surpassed only by cellulose as a naturally occurring organic compound. It is composed of a mixture of two polymers, an essentially linear polysaccharide – amylose (Figure 2-1) and a highly branched polysaccharide-amylopectin (Figure 2-2). The building block for both consituent polymers of starch is the glucose monomer. A starch chain is typically made up of between 500 and 2000 glucose units linked in the 1,4 carbon positions (Nolan-ITU, 2002). The level of amylopectin (typically 70%) varies between different starch types, as does the level of amylose (Hedley, 2002).

Figure 2-1: A section of the amylose molecule showing the repeating anhydroglucose unit.

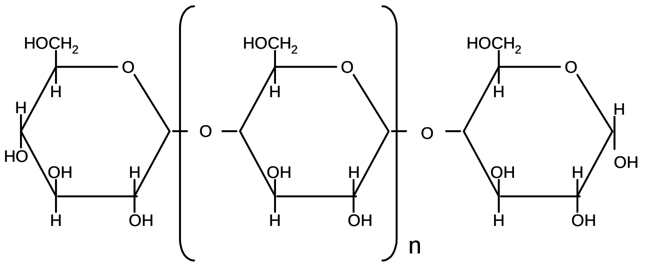
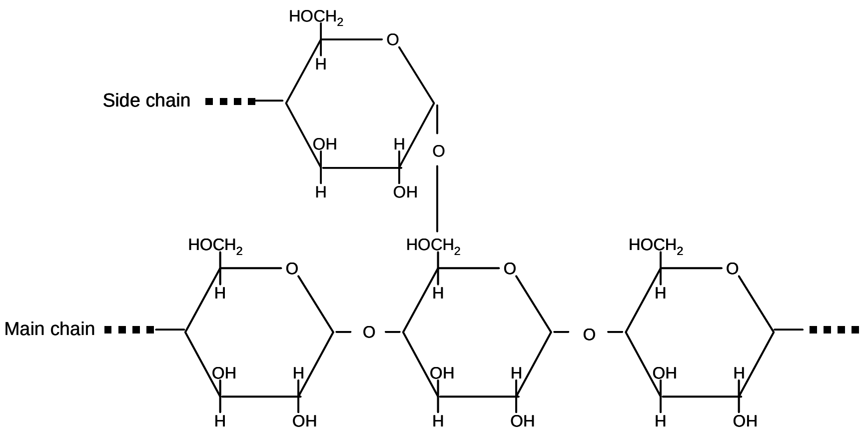


Figure 2-2: A section of the amylopectin molecule showing the two different types of chain linkages.



Starch is unique among carbohydrates because it occurs naturally as discrete granules. This is because the short branched amylopectin chains are able to form helical structures which crystallise (UC, 2003). Starch granules exhibit hydrophilic properties and strong inter-molecular association via hydrogen bonding due to the hydroxyl groups on the granule surface. The melting point of native starch is higher than the thermal decomposition temperature; hence the poor thermal processability of native starch and the need for conversion to a starch polymer which has a much improved property profile.

Commercialised during the last few years, starch polymers today dominate the bio-based polymer market. In 2002, about 30,000 metric tonnes per year were produced and the market share of these products was about 75-80% of the global market for bio-based polymers (Degli Innocenti and Bastioli, 2002). 75% of starch polymers are used for packaging applications, including soluble films for industrial packaging, films for bags and sacks, and loose fill. Leading producers with well established products in the market include Novamont, National Starch, Biotec and Rodenburg.

The starch crops used include corn, wheat, potato, tapioca and rice. Currently, the predominant raw material for the production of starch polymers (as used by Novamont) is corn. Other sources of starch are also being utilised where price and availability permit. Examples include the use of potato starch by BIOP Biopolymer Technologies in Germany and a process based on a potato starch waste stream at Rodenburg Biopolymers in the Netherlands.

Today, co-polymers used for blending or complexing may consititute up to 50% of the total mass of the starch polymer product (Novamont, 2003b). These co-polymers are generally derived from fossil feedstocks. It is envisaged by Novamont that by 2020 it will be possible to produce a polymer based 100% on starch having a similar property profile as these blends of thermoplastic starch and petrochemical copolymers. It is expected that this will be achieved by the development of more efficient chemical and biological starch modification processes (Novamont, 2003b).

The genetic modification (GM) of plants to alter the nature of starch, e.g. the amylopectin potato developed in the mid-1990s by Avebe (Oeko-Institut, 2001) is another possible pathway. However, starch polymer producers in the EU are currently employing a GM-free feedstock policy due to ongoing debate and adverse public opinion relating to GM crops.

2.1.1 Production of starch polymers

Figure 2-3 illustrates the main proprietary technologies and processing steps leading to commercial starch polymer products as found in literature and obtained from private communications with producers. Figure 2-3 is necessarily open to interpretation; e.g. the addition of chemicals leading to alteration of the structure of starch is described variously as ‘chemical modification’ when the starch is in its native form and as ‘reactive blending’ and ‘blending’ when the starch is thermoplastic.

With reference to Figure 2-3, we may distinguish between three main groups of starch polymers emerging from the primary processing step, namely: **Partially Fermented Starch Polymers; Pure Starch Polymers and Modified Starch Polymers**.

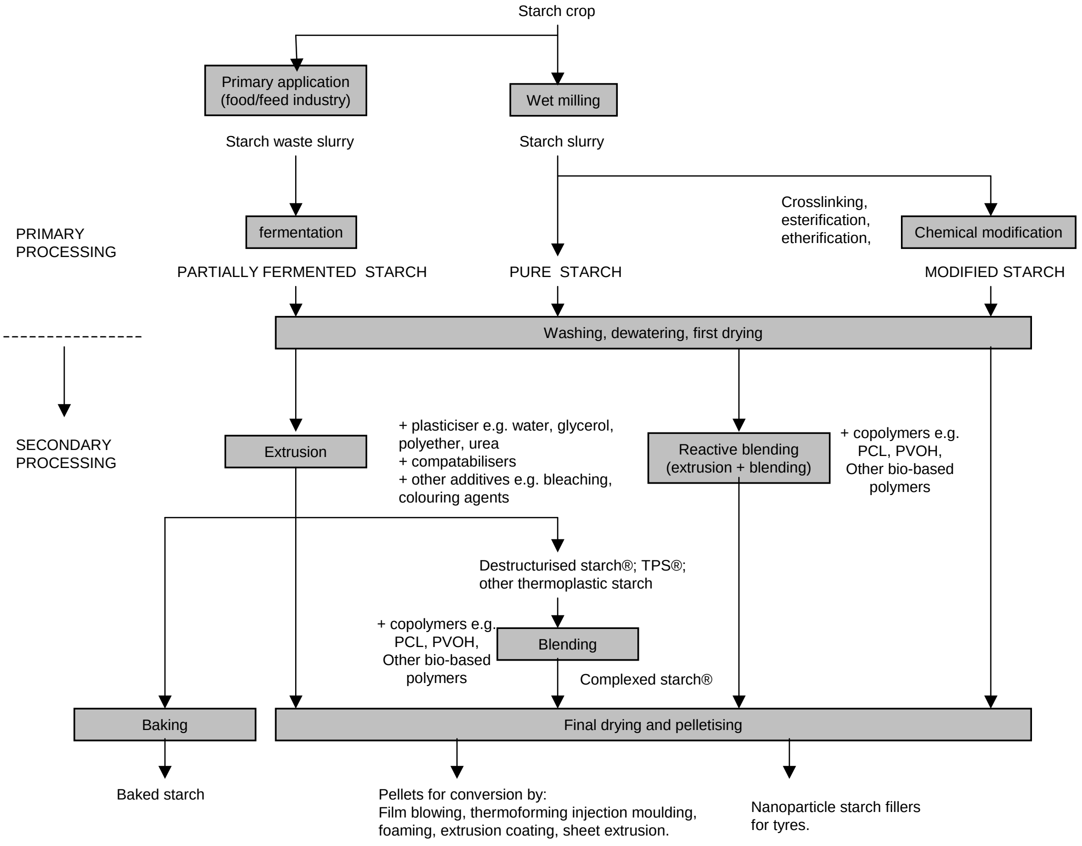
In the production of **Partially Fermented Starch Polymers** (a term used here to refer specifically to the product manufactured by Rodenburg Biopolymers) (Rodenburg, 2003), the raw material is potato waste slurry originating from the food industry. This slurry mainly consists of starch (72% of the dry matter, DM), with the remainder being proteins ($12\%_{DM}$), fats and oils ($3\%_{DM}$), inorganic components ($10\%_{DM}$) and cellulose ($3\%_{DM}$). The slurry is held in storage silos for about two weeks to allow for stabilisation and partial fermentation. The most important fermentation process occurring is the conversion of a (smaller) part of the starch to lactic acid (via glucose) by means of lactic acid bacteria that are naturally present in the feedstock. The product is subsequently dried (10% final water content) and extruded (described below) to obtain thermoplastic properties. To improve the product properties, palm oil and additives such as titanium dioxide (TiO_2) and calcium carbonate ($CaCO_3$) are added in the extrusion step. Finally the material is stabilised by another drying step.

The production of other types of starch polymers begins with the extraction of starch. Taking the example of corn (maize), starch is extracted from the kernel by wet milling. The kernel is first softened by steeping it in a dilute acid solution, coarse ground to split the kernel and remove the oil-containing germ. Finer milling separates the fibre from the endosperm which is then centrifuged to separate the less dense protein from the more dense starch. The starch slurry is then washed in a centrifuge, dewatered and dried prior to extrusion or granulation (National Starch and Chemical Company, 2003).

Either prior or subsequent to the drying step, and often at a separate location to the starch production plant, the starch may be processed in a number of ways to improve its properties. **Modified starch** is starch which has been treated with chemicals so that some hydroxyl groups have been replaced by e.g. ester or ether groups. High starch content plastics are highly hydrophilic and readily disintegrate on contact with water. Very low levels of chemical modification can significantly reduce hydrophilicity, as well as change other rheological, physical, and chemical properties of starch. Crosslinking, in which two hydroxyl groups on neighbouring starch molecules are linked chemically is also a form of chemical modification. Crosslinking inhibits granule swelling on gelatinization and gives increased stability to acid, heat treatment, and shear forces (Foodstarch, 2003). Chemically modified starch may be used directly in pelletised or otherwise dried form for conversion to a final product.

Pure Starch Polymers are those materials which are not altered (in the primary processing step, see Figure 2-3) by fermentation or chemical treatment. As for the Rodenburg (partially fermented starch) material, these polymers are always subject to further processing by extrusion and/or blending to obtain a thermoplastic material.

Figure 2-3: Starch polymer production technologies



After the first drying step (Figure 2-3), a secondary processing stage may be identified. This is the stage during which starch is converted to a thermoplastic material either by extrusion only, by sequential steps of extrusion and blending, or by a combined extrusion/blending step. The first group of materials emerging from the secondary processing stage – thermoplastic pure starch polymers, e.g. TPS from Biotec - are of somewhat limited usefulness due to the hydrophilicity and mechanical properties of pure thermoplastic starch. The second group thermoplastic starch blends – complexed starch - is most widespread and is produced by a few companies (e.g. Novamont) based on a variety of patents. The third group, products of reactive blending, is listed separately but it is not known if this technology is used commercially.

Starch may be **extruded** with a plasticiser in a single or twin screw extruder to produce a thermoplastic material with greatly enhanced processability compared to granular starch. The increase in temperature during extrusion increases the mobility of starch granules and leads to melting of the crystalline structures. The granules swell and take up the plasticiser, shear opens the granule, the starch dissolves and fragments, and intramolecular rearrangement takes place (Hood, 2003). Compounders (fillers, additives etc.) can be integrated into the extrusion process to provide the final resin product in one step. During the extrusion process, plasticisers such as glycerol, polyethers and urea may be added to reduce the intermolecular hydrogen bonds and to stabilize product properties. By lowering the water activity, plasticisers also limit microbial growth (Weber, 2002).

Blending, meaning the addition of other polymers to thermoplastic starch, may take place during extrusion (‘reactive blending’) or after extrusion. To illustrate: a technology has been developed for blending of starch with poly(ε-caprolactone) (PCL) by sequential extrusion steps (SINAS, 2003): ε-caprolactone is polymerised, the resulting polymer is reactively blended with thermoplastic starch, then in a third extrusion step, compatabilisers are added to obtain plastic starch dispersed in a continuous PCL matrix phase. The properties of the resulting film are comparable to low density polyethylene film (LDPE) and better than pure PCL film.

Another important use of blending is to formulate soluble polymers. Starch blended with poly(vinyl alcohol) (PVOH) exhibits water solubility in approximately 3 minutes and is typically used to produce loose fills (Nolan-ITU, 2002).

Novamont, the major producer of starch polymers, has patented certain aspects of starch extrusion technology. **Destructured starch** is formed during the extrusion process under certain conditions of temperature, pressure, shear, limited water and sufficient time such that the native crystallinity and granular structure of amylase & amylopectin are almost completely destroyed. The resulting material is called a "molecular dispersion of starch and water" (MDS) (Degli Innocenti and Bastioli, 2002). MDS products are molecularly homogeneous (with both amylose and amylopectin dispersed uniformly throughout the material), have no native crystallinity and essentially no granular structure, have relatively high molecular-weight amylopectin, are not brittle or friable and have superior mechanical properties. **Complexed starch** is formed when destructurised starch is blended with certain macromolecules (e.g. PCL) which are able to form a complex with amylose. The complexing agent forms a single helix with amylose, while the amylopectin does not interact and remains in its amorphous state. The starch ‘supramolecules’ are specified by the ratio of amylose to amylopectin, the nature of additives, processing conditions and the nature of complexing agents (Degli Innocenti and Bastioli, 2002).

Conversion technologies

Starch polymers can be converted into finished product on slightly modified standard thermoplastic resins machinery. Conversion technologies in use include film blowing, extrusion, thermoforming, injection moulding and foaming. Novamont is also looking into extrusion coating of fibres and diapers and sheet extrusion (Novamont, 2003). Apart from other applications, complexed starch is used as a biopolymeric filler to substitute partially carbon black in tyres (between 5-10 % w/w; replacing carbon black and silica: 10-20% w/w). This technology has been jointly developed by Goodyear and Novamont and it is being applied by Goodyear for the production of a certain type of tyre (see Chapter 2.1.4).

2.1.2 Properties

The majority of starch polymers are produced via extrusion and blending of pure or modified starch (see Figure 2-3). The chemical, mechanical and thermal properties of a number of these are given in Table 2-3.

Table 2-3: Properties of starch polymers

	Starch (>85%)/ co-polyester **Mater-Bi®** *NF01U*[1,4]	Starch/ PCL **Mater-Bi®** *ZF03U/A*[1]	Starch/ cellulose acetate **Mater-Bi®** *Y101U*[1]	Starch/ cellulose acetate **Bioplast®** *GF105/30*[2]	Modified Starch **Cornpol®**[3]
Physical properties					
Melt flow rate (g/10 min)	2-8[b]			5-9	5-6
Density (g/cm^3)	1.3	1.23	1.35	1.21	1.2
Transparency (%)					
Mechanical properties					
Tensile strength at yield (MPa)	25	31	26	44, 38[a]	30
Elongation at yield (%)	600	900	27	400, 500[a]	600-900
Flexular Modulus (MPa)	120	180	1700		10-30
Thermal properties					
HDT (°C)					85-105
VICAT Softening point (°C)				65	105-125
Melting Point (°C)	110	64			

[1] Gross and Kalra (2002):
2 Biotec (2003);
[3] Japan Corn Starch (2003);
[4] Basitoli (2003)
[a]MD, TD respectively;
[b]unspecified grade of Mater-Bi for film.

Chemical and physical properties

Starch polymers are partially crystalline but much less so than cellulosics. The density of starch polymers is higher than most conventional thermoplastics and also higher than most bio-based polymers, decreasing its price competitiveness on a volume basis. Thermoplastic starch and starch blend films have reasonable transparency. Starch polymers have low resistance to solvents and oil (Petersen et al. 1999) although this may be considerably improved by blending e.g. with PCL.

Mechanical and thermal properties

The mechanical properties of starch polymers are in general inferior to petrochemical polymers. Starch polymers are reasonably easy to process but are vulnerable to degradation. In starch blends, the glass transition point generally decreases (corresponding to increasing softness) with increasing content and/or chain length of the polyester component.

Other Properties

The range of possible applications for starch polymers is restricted by their sensitivity to moisture and water contact and high water vapour permeability. Other barrier properties (oxygen and carbon dioxide) are moderate to good. Starch polymers are biodegradable; although too high a copolymer content can adversely affect biodegradability due to the complex interaction of starch and polyester at the molecular level (Degli Innocenti and Bastioli, 2002). Starch polymers are intrinsically antistatic.

2.1.3 Technical substitution potential

Modified Starch Polymers

The potential for starch polymers (mainly: Modified Starch Polymers) to substitute for other polymers, as indicated in Table 2-4, is seen to be greatest for the polyolefins, namely low density polyethylene (LDPE), high density polyethylene (HDPE) and polypropylene (PP). Blends of thermoplastic starch with synthetic polyesters in particular come closest to achieving the mechanical properties of LDPE and HDPE, as well as polystyrene (PS).

Table 2-4: Technical substitution potential for starch polymers (Modified Starch Polymers)
++ full substitution + partial substitution - no substitution

	PVC	PE-HD	PE-LD	PP	PS	PM-MA	PA	PET	PBT	PC	POM	PUR	ABS	non-poly
Novamont[1]	(-)	+	+	+	+	(-)	(-)	(-)	(-)	(-)	(-)	+	(-)	+
[2]Japan Corn Starch[1]	+	+	+	+	+	-	-	-	-	-	-	-	+	-

[1] Novamont (2003b),

[2] Japan Corn Starch (2003).

Good mechanical performance and the ability to resist static cling, combined with biodegradability and water solubility, have enabled starch loose fill for packaging, which is a blend of TPS and PVOH to successfully compete for a number of years already with expanded polystyrene (EPS) products (USDA, 1996). In the production of foams and soluble items there is further potential for substitution for EPS, polyurethane (PUR) and paper (Novamont, 2003b). Another established and growing area for substitution is the use of starch as a filler for automobile tyres (Novamont, 2003b; see below).

Partially Fermented Starch Polymers

Partially Fermented Starch Polymers have so far been used mainly for less demanding applications (in terms of mechanical properties, appearance etc.) for which virgin polymers are not necessarily required.

2.1.4 Applications today and tomorrow

Modified Starch Polymers

As shown in Table 2-5, **packaging** is now the dominant application area for Modified Starch Polymers, amounting to 75% of the total market share for starch polymers. Starch-PCL blends are used in applications including biodegradable film for lawn and leaf collection compost bags. They are also used to laminate paper, cardboard and cotton and other natural fibres. Starch blends are also used for packaging films, shopping bags, strings, straws, tableware, tapes, technical films, trays and wrap film (Biotec, 2003). The relatively high water vapour permeability of starch polymers is useful in applications such as fog-free packaging of warm foodstuffs.

Applications in the **agricultural** sector include starch-PCL blends for agricultural mulch film, planters, and planting pots. Further novel applications include materials for encapsulation and slow release of active agents such as agrochemicals (Degli Innocenti and Bastioli, 2002).

Other small-volume or emerging applications include starch-PVOH blends for diaper backsheets, soluble cotton swabs and soluble loose fillers. Other starch blends are used for cups, cutlery, edge protectors, golf tees, mantling for candles and nets.

In the **transportation** sector, Goodyear has been using the starch Mater-Bi filler BioTRED since 2001 in its GT3 tyre (sold as EcoTyre). Starch filler is also used in tyres for the Ford Fiesta in Europe and in BMWs (Degli Innocenti and Bastioli, 2002). Benefits include lower rolling resistance, noise reduction, reduced fuel consumption and CO_2 emissions, and reduced manufacturing energy requirements (Ilcorn, 2003). There is very high potential for further growth of starch polymers in this application (Novamont, 2003b). Based on a variety of sources we have estimated the amount of carbon black used as filler in tyres to lie in the order of magnitude of 1 million tonnes in the EU (between 0.5 and >1.2 million tonnes). In the case of 20% (50% seems also technically possible) weight replacement of carbon black by starch polymers its total market potential would be in the order of 0.5 million tonnes starch polymers. Hence, for example a 50% penetration rate by 2020, would translate into 250 kt of starch polymers for this purpose.

Table 2-5: Main applications for starch polymers – share of interviewed company's[1] total production by market sector (scope: EU 15; without starch as filler)

Sector	% of total production today	% of total production in 2020[2]
Packaging	75 %	N/A
Building	0 %	N/A
Agriculture	25 %	N/A
Transportation	? %	N/A
Furniture	0 %	N/A
Electrical appliances and electronics (E&E)	0 %	N/A
Houseware	0 %	N/A
Others	0 %	N/A
Total	100 %	100%

[1] Novamont (2003);

[2] Data not available(N/A) for 2020.

Partially Fermented Starch Polymers

Rodenburg's material Solanyl is currently used practically exclusively in injection moulding. Apart from the production of flower pots it is used for packaging and transport (e.g. CD covers) and for certain leisure articles that make use of the feature of biodegradability (e.g., golf pins).

2.1.5 Current and emerging producers

Novamont S.p.A., located in Novara, Italy, is the leading European company and pioneer in the field of bio-based polymers and now works in starch polymers. Novamont started its research in the area of starch materials in 1989 as part of the chemical group Montedison. Novamont's objective was to develop materials from natural sources, with in-use performances similar to those of conventional plastics and compostability similar to pure cellulose.

In 1996 Novamont was acquired by Banca Commerciale Italiana and Investitori Associati II. From 1994 to 1997 Novamont increased its turnover by factor of more than 5, reaching actual sales of approximately USD 10 million. In 1997 a new production line was added, doubling production capacity of Mater-Bi® from 4,000 t p.a. to 8,000 t p.a. More recently a new 12,000 t p.a. line was added, bringing total on-site production capacity to 20,000 t.p.a. An additional 15,000 t.p.a. (mostly loose fills) is produced off-site under license agreements for which Novamont shares the technology license agreement with the **National Starch and Chemical** Company. Novamont's direct sales in 2002 amounted to €25 million and it is expected that sales will increase to €30 million in 2003 (Novamont, 2003b).

Novamont has invested in total more than €75 million in R&D and technology (Novamont, 2002). It holds more than 60 patents relating to starch materials technologies, particularly in the area of complexing of starch with synthetic and natural polymers and additives. Its patent portfolio also covers destructurised starch technologies developed by Warner Lambert and acquired by Novamont in 1997. Novamont also acquired the film technology of Biotec in 2001, including an exclusive license of Biotec's patents on thermoplastic starch in the films sector (Degli Innocenti, 2002).

The German company **Biotec** produces about 2000 t.p.a. of thermoplastic starch resins and owns a large number of patents for extrusion technologies, blending and modifying of thermoplastic processable starch (TPS). Biotec has pilot scale facilities for blown film extrusion, sheet extrusion, thermoforming and injection molding, and production lines for compounding, granulating and mixing. It produces a range of plasticiser-free thermoplastics under the brand-name Bioplast®, and a pure thermoplastic starch, Bioplast® TPS (Biotec, 2003).

BIOP Biopolymer Technologies in Dresden, Germany, manufactures a pure granulate and blends from potato starch under the trade name BIOPar®. It has commissioned a 10,000 t.p.a. production facility and is targeting scale-up to 150,000 t.p.a. between the end of 2004 and 2006 (BIOP, 2003).

Potatopak, a UK company, manufactures starch derivative replacement products for polystyrene and various plastic packaging items (Potatopak, 2003). **Avebe** and **Earthshell** manufactures a product containing limestone, starch and cellulose fibre using similar starch baking technology.

In Japan, **Japan Corn Starch** produces a modified starch under the brand name Cornpol®. The company is involved in basic R&D as well as pilot/demonstration projects. The interviewed representative was not at liberty to disclose any commercialisation plans, nor the target production scale (Japan Corn Starch, 2003). Also in Japan, **Nihon Shokuhin Kako** produces a starch synthetic with the name Placorn® - again, no production volume data could be obtained. According to Japan's Biodegradable Plastic Society, starch polymers, including Mater-Bi imported from Novamont, currently comprise about 30% of the total consumption of biodegradable plastics in Japan, i.e. 3 kt of a total 10 kt in 2002.

Rodenburg Biopolymers is to its knowledge the only manufacturer of Partially Fermented Starch Polymers. The company is located in Oosterhout, the Netherlands, and produces as their sole product Solanyl®, an extruded granule of thermoplastic potato starch. Rodenburg's aim is to profitably utilize potato by-products by converting them into polymers. Research began in 1997 and by 2001 a 7000 t.p.a. pilot plant was in use. A 40,000 t.p.a. plant is currently being brought on line. At full capacity, Rodenburg will be the world's largest producer of starch polymer in tonnage terms. The company is targeting applications where biodegradability is a key requirement, as for example in plastics goods for the horticultural industry. At €1 per kg, Solanyl® is price-competitive with conventional oil-based plastics. For most applications it is, however, blended with synthetic or bio-based polyesters (to reduce hydrophilicity and improve processability; INFORRM, 2003) which increases the total cost per kg of polymer blend.

2.1.6 Expected developments in cost structure and selling price

Selling price

The current price for Modified Starch Polymers ranges from €1.50 per kg for injection moulding foams to €4.50 per kg for films and specialty products; an averaged price is around **€2.50-3.00** per kg (Novamont, 2003b). Rodenburg's Partially Fermented Starch Polymer "Solanyl" is sold at a price of **€1.00** per kg (Rodenburg, 2003).

Cost structure

The cost of starch in Europe is twice as high as in the US. According to Bastioli (2003), the cost of native starch is not a driver. The main cost component is rather the modification of starch (complexing, destructurising), an area in which there is considerable potential for improvement.

Expected price developments

The price is expected to follow the cost of modification of starch; thus there is also considerable scope for the price to decrease in the future.2.1.7 Environmental impacts

Modified Starch Polymers

For starch polymers, Dinkel et al. (1996), Würdinger et al. (2001), Estermann et al. (2000) and Patel et al. (1999) conducted environmental assessments for pellets (i.e., primary plastics) and/or for end products, especially films, bags and loose-fill packaging material. Table 2-6 compares starch polymer pellets with different shares of petrochemical copolymers. Information about the composition of the blends was provided by starch polymer manufacturers (Novamont, Biotec). It was assumed that both the starch polymers and polyethylene are burned in municipal solid waste incineration (MSWI) plants after their useful life. No credits have been assigned to steam and/or electricity generated in waste-to-energy facilities. According to Table 2-6 starch polymers offer saving potentials relative to polyethylene in the range of **24-52 GJ/t** plastic and **1.2-3.7 t CO_2/t** plastic depending on the share of petrochemical co-polymers[3]. These values are confirmed by the other studies mentioned above (for details see Appendix 3 in Chapter 8). These other studies show similarly broad ranges which are caused not only by different starch/copolymer blends but also different waste treatment and different polyolefin materials used as reference (Appendix 3). For **starch polymer pellets** energy requirements are mostly **25%-75%** below those for polyethylene (PE) and greenhouse gas emissions are **20%-80%** lower. Except for eutrophication starch polymers (both TPS and copolymers) score better than PE also for all other indicators covered by the LCA being the sole exception.

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[3] The savings are more than 4 GJ higher if pure LDPE (80.6 GJ/t according to Boustead, 1999) is chosen as the petrochemical counterpart. It should be borne in mind that there are still considerable uncertainties also for these petrochemical polymers (Patel, 2003).

As Table 2-6 further shows, the environmental impact of starch polymers generally decreases with lower shares of petrochemical copolymers. However, the application areas for pure starch polymers and blends with small amounts of copolymers are limited due to inferior material properties. Hence, blending can extend the applicability of starch polymers and thus lower the overall environmental impact at the macroeconomic level.

Ideally, the environmental impacts should be determined for **final products** in order to account for differences in efficiencies in the conversion stage, differences in material properties (e.g. density). This, however, necessitates limiting study to a few end products only. LCA results for important starch polymer end products are given in Table 2-6 (for more details see Appendix 3). The results for **starch polymer loose fills** differ decisively depending on the source. Much of these differences can be explained by different assumptions regarding the bulk density of the loose fills (see second column in Appendix 3) and different approaches for the quantification of the ozone depletion potential (inclusion versus exclusion of NO_x). It therefore seems more useful to compare the results of each study separately. One can conclude from both Estermann et al. (2000) and Würdinger et al. (2002) that starch polymer loose fills generally score better than their equivalents made of virgin EPS. Greenhouse gas (GHG) emissions represent an exception where the release of CH_4 emissions from biodegradable compounds in landfills results in a disadvantage for starch polymers (only according to Würdinger et al., 2002). The other sources reviewed may not have taken this emission source into account.

By analogy to loose fills, the range of results for **starch polymer films and bags** is to a large extent understandable from the differences in film thickness. Taking this factor into account, the environmental impacts of the starch films/bags are lower with regard to energy, GHG emissions and ozone precursors. The situation is less clear for acidification. For eutrophication, PE films tend to score better.

Since all data in Table 2-6 and in Appendix 3 refer to the current state-of-the-art, technological progress, improved process integration and various other possibilities for optimisation are likely to result in more favourable results for biopolymers in the future.

Table 2-6: Energy use and greenhouse gas (GHG) emissions of (Modified) Starch Polymer pellets and their petrochemical counterparts (Patel et al., 1999)

	Energy[1] in MJ/kg			GHG emissions[2] in kg CO_2 eq./kg		
	Pchem. Polymer[3]	Bio-based polymer	Energy savings	Pchem. Polymer[3]	Bio-based polymer	Emission savings
TPS	76	25	51	4.8	1.1	3.7
TPS + 15% PVOH	76	25	52	4.8	1.7	3.1
TPS + 52.5% PCL	76	48	28	4.8	3.4	1.4
TPS + 60% PCL	76	52	24	4.8	3.6	1.2
Starch polymer foam grade	76	34	42	4.8	1.2	3.6
Starch polymer film grade	76	54	23	4.8	1.2	3.6

TPS = thermoplastic starch

[1] Non-renewable energy

[2] Emissions refer to incineration in all cases. Exception: Composting has been assumed for starch polymer film grades.

[3] 50% LLDPE + 50% HDPE according to Boustead (1999).

As mentioned above the use of **starch polymers as fillers in tyres** is a special application of Modified Starch Polymers. These tyres are reported to have various functional advantages, the most important being controlled stiffness, improved wet skid performance, lower weight and reduced rolling resistance. As Table 2-7 shows, especially the latter feature leads to lower CO_2 emissions: Savings due to lower rolling resistance, which result in fuel savings in the use phase, exceed cradle-to-factory gate emission reduction by factors of 23 to 26. The total savings according to Table 2-7 represent about 2% (for 3.53 g CO_2/km) to 5% (for 9.52 g CO_2/km) of the average CO_2 emissions of a passenger car (Corvasce, 1999).

Table 2-7: CO_2 emission reduction potential of tyres with biopolymeric fillers (Corvasce, 1999)

	CO_2 reduction compared to conventional tyres[1)] g CO_2/km	
	20% weight replacement of carbon black	50% weight replacement of carbon black
Use of starch-based raw materials[2)]	0.15	0.35
Tyre weight reduction[3)]	0.03	0.25
Tyre rolling resistance reduction[3)]	3.35	8.92
Total	3.53	9.52

[1)] Averaged values over 30 000 km; tread weight 3.0 kg.

[2)] Cradle-to-factory gate: Emission of fossil CO_2 during processing minus carbon sequestration in starch during plant growth.

[3)] Use phase

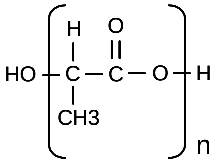
Partially Fermented Starch Polymers

A first assessment of the environmental profile of Rodenburg's polymers Solanyl has been conducted at Utrecht University (unpublished). This indicates that the primary energy use for the production of Solanyl is in the range of that required for making recycled polyethylene (PE) from plastic waste (about 9 GJ/t). This would mean that Partially Fermented Starch Polymers can be produced with only little more than one third of the energy needed for the manufacture of Modified Starch Polymers. According to these preliminary results the production of Solanyl (cradle-to-factory gate primary energy requirements ca. 9 GJ/t) is about four times less energy intensive than the production of virgin PE with waste management in a highly efficient waste-to-energy facility (cradle-to-grave energy requirements at least 34 GJ/t).

2.2 Polylactic acid (PLA)

Since the setup of Cargill Dow's polylactic acid (PLA) production plant in 2002, PLA has become the second type of bio-based polymers that has been commercialised and produced on a large scale. PLA (see Figure 2-4) is an aliphatic polyester produced via polymersation of the renewable fermentation product lactic acid.

Figure 2-4: PLA molecule



$$HO-\left[\overset{H}{\underset{CH3}{C}}-\overset{O}{\overset{\|}{C}}-O\right]_n-H$$

PLA has excellent physical and mechanical properties, making it a good candidate for substitution for petrochemical thermoplasts, and it can be processed on existing machinery with only minor adjustments (Galactic, 2003). While the high price for PLA has long restricted its use to medical and specialty applications, recent breakthroughs in lactic acid fermentation technology have opened up possibilities for the production of PLA in bulk volumes.

Lactic acid, 2-hydroxypropionic acid, is the simplest hydroxycarboxylic acid with an asymmetrical carbon atom. Lactic acid may be produced by anaerobic fermentation of carbon substrates, either pure (e.g. glucose, lactose) or impure (e.g. starch, molasses) with micro-organisms such as bacteria or certain fungi (Galactic, 2003). Lactic acid produced by fermentation is optically active; specific production of either L (+) or D (–) lactic acid can be determined by using an appropriate lactobacillus (Chahal, 1997).

The range of raw materials suitable for lactic acid fermentation includes hexoses (6-carbon sugars, of which D-glucose is the primary example) together with a large number of compounds which can be easily split into hexoses, e.g., sugars, molasses, sugar beet juice, sulfite liquors and whey, as well as rice, wheat, and potato starches. In the future, it is expected that hydrolysis of lignocellulosics - i.e. woody or herbaceous biomass as it is available from wood, straw or corn stover - will become a viable pathway through technological advances (e.g. in enzymatic processes), together with pressures on resources driving the increased utilization of agricultural waste products.

PLA was first synthesized over 150 years ago but due to its instability in humid conditions, no immediate application was found and it was not until the 1960s that its usefulness in medical applications became apparent. Efforts to develop PLA as a commodity plastic were first made in the late 1980s and early 1990s by Dupont, Coors Brewing (Chronopol) and Cargill. All three companies ran large research and development programs to explore the possible bulk applications for lactic acid, lactide and PLA (Södergård and Stolt, 2002). While DuPont and Chronopol terminated their efforts, Cargill went on to develop a continuous process for high purity lactide production based on reactive distillation.

The development of PLA for bulk applications began in 1994 when Cargill first produced PLA in its 6000 t.p.a. semi-works plant in Savage, Minnesota, U.S. In 1997, Cargill and Dow Chemical formed a joint collaboration agreement to explore the market potential for PLA. In January 2000 the joint venture **Cargill Dow** LLC was formed for the purposes of reaching commercial-scale production of PLA and developing the market for PLA products. In spring 2005 Dow announced to pull out of this enterprise in order to concentrate on a product portfolio with a shorter business life cycle. However, as the report covers a period before that opint in time, the enterprise is referred to as Cargill Dow in the following. This makes sense, as the PLA production is continued by Cargill.

2.2.1 Production of PLA

Lactic acid from a carbon substrate

The first step in the process is extraction of starch from biomass. This is typically achieved by wet milling of corn. The starch is then converted to sugar by enzymatic or acid hydrolysis. The sugar liquor is then fermented by bacteria e.g. of the Homolactic Lactobacteriaceae family. L-lactic acid is produced from pyruvate under oxygen limiting conditions via the enzyme lactate dehydrogenase according to the equation (Pi = inorganic phosphate) (Chahal, 1997):

Glucose + 2 ADP + 2 Pi $\rightarrow$ 2 Lactic acid + 2 ATP

Conversion is typically greater than 95% on carbohydrate substrate (Datta et. al., 1995 *in Wilke, 1999*). The fermentation can be performed in either a batch or a continuous process. The lactic acid has to be separated from the fermentation broth and in most cases purified prior to polymerisation[4,5]. The most common purification process involves neutralisation with a base followed by filtration, concentration and acidification (Södergård and Stolt, 2002). The acidification step involves treating soluble calcium lactate with sulfuric acid in order to generate the free acid, producing large amounts of gypsum ($CaSO_4.2H_2O$) as a by-product. The free acid is then purified by carbon treatment and ion exchange which, however, does not yield the thermostable product quality required for chemical synthesis. Thermostable fermentation lactic acid is manufactured by esterification, distillation, subsequent hydrolysis of the ester and recovery of the alcohol by evaporation (Wilke, 1999).

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[4] Losses in the product recovery step amount to approximately 5 to 10%, bringing the overall yield (carbon basis) on purified lactic acid to about 85-90%, with possibilities for further improvement in both the fermentation step and product recovery. Assuming 100% conversion of lactic acid to PLA, yield (mass basis) in the polymerisation step is 72.1/90.1 = 80%, bringing the overall yield (carbon basis) in the vicinity of 70%.

[5] While it is important to keep in mind that there is an economic optimum for each process described in this report with regard to substrate-related yield, productivity, fermentation broth concentration and % loss in the product recovery steps; and that this optimum will change with time due to technological developments. It has therefore been chosen in the present study to take a more meso level approach, compiling available data at the industry level and projecting this at the industry and macro level with the use of experience curves (Section 3.3).

Since the early 1980s several companies have worked on new, energy-saving recovery technologies to manufacture pure, thermostable lactic acid. Among such concepts, electrodialysis has been studied in detail but could not be converted to a commercial scale. A low temperature esterification process using pervaporation has also been described (Datta and Tsai, 1998 in: Wilke, 1999). Liquid/liquid extraction is another potential lactic acid recovery route. Separation techniques including ultrafiltration, nanofiltration, and ion-exchange processes may also be employed to further purify the lactic acid (Södergård and Stolt, 2002).

Lactic acid may also be produced chemically from petrochemical raw materials such as acetylene or ethylene. In this case the product is a racemic mixture, having amorphous properties with possible applications as biodegradable adhesives. In recent years the fermentation approach has become more successful because of the increasing market demand for lactic acid which is naturally produced.

PLA from lactic acid

Two main routes have been developed to convert lactic acid to high molecular weight polymer: the indirect route via lactide, the product of which is generally referred to as poly(lactide), and direct polymerisation by polycondensation, producing poly(lactic acid). Both products are generally referred to as PLA (Södergård and Stolt, 2002).

The first route, employed by Cargill Dow, is a continuous process using ring-opening polymerisation (ROP) of lactide (Gruber and O'Brien, 2002). Condensation of aqueous lactic acid produces low molecular weight PLA prepolymer (< 5000 Dalton, see Figure 2-5). The prepolymer is then depolymerised by increasing the polycondensation temperature and lowering the pressure, resulting in a mixture of lactide stereoisomers. An organometallic catalyst e.g. tin octoate is used to enhance the rate and selectivity of the intramolecular cyclisation reaction. The molten lactide mixture is then purified by vacuum distillation. In the final step, high molecular weight PLA(>100000 Dalton) polymer is produced by catalysed ring-opening polymerization in the melt. Any remaining monomer is removed under vacuum and recycled to the start of the process. By controlling the ROP process chemistry it is possible to select the stereoform of the lactide intermediate; and thereby also the properties of the resultant PLA. Usually, high purity L,L-lactide is the desired intermediate for the production of PLA.[6]

In the second route, used by Mitsui Toatsu, lactic acid is converted directly to high molecular weight PLA by an organic solvent-based process with the azeotropic removal of water by distillation. (Gross and Kalra, 2002).

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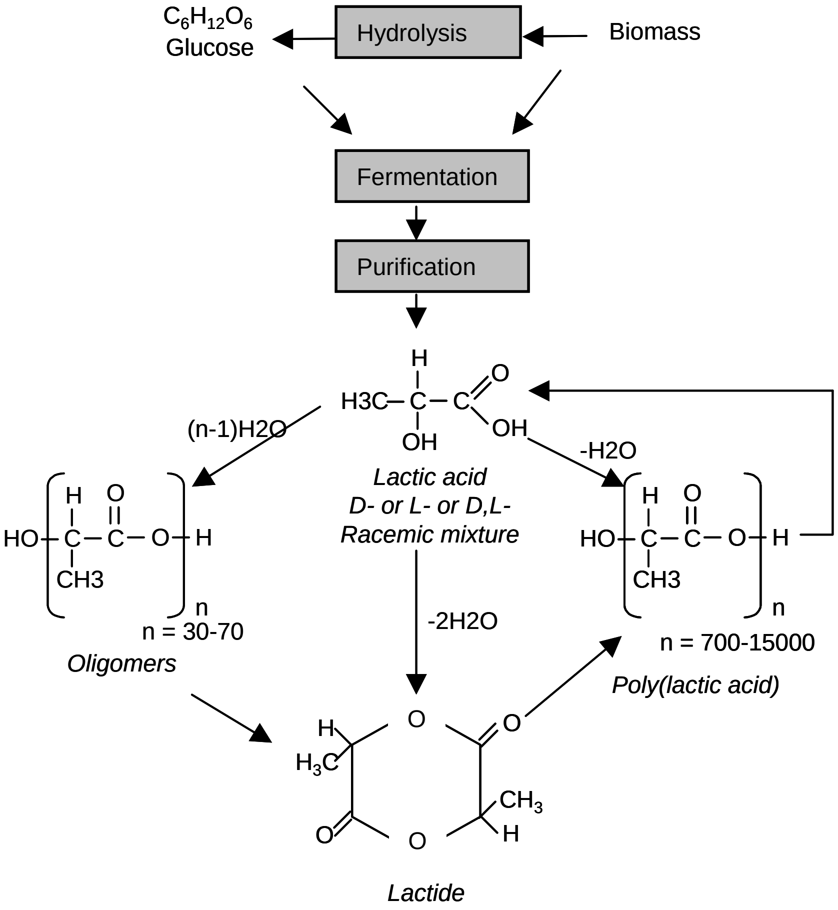
[6] Polymerisation of L,L-lactide results in the stereoisomeric form poly(L-lactide) or poly(L-lactic acid), more correctly denoted as PLLA but is herein more simply referred to as PLA.

Figure 2-5: Production of PLA from biomass



Copolymers, blends and composites

To obtain PLA with improved properties, lactic acid may be copolymerised with other cyclic monomers such as ε-caprolactone (PCL). Reaction conditions are similar to that for the ROP process (Gruber and O’Brien, 2002).

Alloys (blends) of PLA and other bio-based polymers such as starch or polyhydroxyalkanoates (PHAs) may be obtained by blending. PLA/PHA alloys show particular promise and are the subject of ongoing investigation (P&G, 2003; as discussed further in Chapter 2.4.2). Blending of PLA with natural fibres such as kenaf is another possibility.

Conversion technologies

PLA can be converted to end product using slightly modified standard industrial machinery for thermoplastics (Gruber and O’Brien, 2002) by techniques including thermoforming, injection moulding, blow moulding extrusion and importantly, film extrusion. High-value films and rigid thermoformed containers are the most promising bulk applications. Fibre extrusion by melt spinning is gaining importance as PLA finds applications in the nonwovens industry.

Additives

While the bulk of any plastic material is the polymer or resin, a small part is additives. Additives are used to impart the plastic with properties such as improved flow characteristics, easy release from the mould, resistance to fire, UV stability, oxygen stability, strength and flexibility and colour. In the case of PLA, required additives include anti-statics (to combat electrostaticity of PLA foil); biodegradable organic pigments, inks and coatings, biodegradable mould detaching agents; and low-cost vapour deposition to reduce moisture permeability. Some of these additives are not yet available or require further development to meet performance criteria (Treofan, 2003).

2.2.2 Properties

The property profile of PLA (see Table 2-8) is in certain aspects similar to synthetic thermoplastics (mechanical strength, elastic recovery and heat sealability); it shares other properties in common with bio-based polymers (biodegradability, dyeability, barrier characteristics) while a number of its properties are more typical of non-polymeric materials; e.g. deadfold/twist retention similar to foil or paper. For this reason, PLA is sometimes described as a 'new paradigm' (Dorgan, 2003) in the bulk application polymer field.

Table 2-8: Properties of PLA

	NatureWorks® PLA[1]	Biomer® L9000[2]
Physical properties		
Melt flow rate (g/10 min)	-[a]	3-6
Density (g/cm^3)	1.25	1.25
Haze	2.2	
Yellowness index	20-60	
Mechanical properties		
Tensile strength at yield (MPa)	53[3]	70
Elongation at yield (%)	10-100[b]	2.4
Flexular Modulus (MPa)	350-450	3600
Thermal properties		
HDT (°C)	40-45, 135[d]	
VICAT Softening point (°C)	-[c]	56
GTT (°C)	55-65	
Melting point (°C)	120-170[4]	

[1] Data not otherwise referenced obtained from Cargill Dow (2003);

[2] Biomer (2003);

[3] Brandrup (1999), p.163;

[4] Woodings (2000).

[a] Due to PLA's moisture sensitivity, a more accurate test RV t-test method 4.3-2.4;

[b] Oriented and sheet respectively, non-blended;

[c] close to GTT;

[d] amorphous and crystalline respectively.

Chemical Properties

The molecular weight, macromolecular structure and the degree of crystallisation of PLA vary substantially depending on reaction conditions in the polymerisation process. Of the three possible isomeric forms, poly (L-lactic acid) and poly (D-lactic acid) are both semi-crystalline in nature, and poly (meso-lactic acid) or poly (d,l-lactic acid) is amorphous. By varying the relative content of the stereoforms, the morphology changes from resins that always remain amorphous to amorphous resins that can be crystallized during manufacturing. Racemic PLA - synthesised from petrochemicals - is atactic, i.e. it exhibits no stereochemical regularity of structure, is highly amorphous and has a low glass transition temperature. Amorphous grades of PLA are transparent. The molecular weight of PLA varies from 100,000 to 300,000; this range is similar to that for PET (170,000 to 350,000). With increasing molecular weight of PLA (as for polymers in general), strength increases due to the decrease in relative motion of the chains as they become longer. In addition, the resistance to solvents increases and the melt point (T_m) and the glass temperature (T_g) increase. The melt viscosity increases and the ease of fabrication (moulding, extrusion and shaping) decreases (McGraw-Hill, 1997).

Physical Properties

The specific gravity of PLA (1.25 g/cm^3) is lower than that of PET (1.34 g/cm^3), but higher than HIPS (1.05 g/cm^3) and also higher to many other conventional polymers which have specific gravity in the range of 0.8 to 1.1. PLA is reasonably transparent and has high gloss and low haze. The optical properties of PLA are sensitive to additive and fabrication effects (Gruber and O'Brien, 2002); in particular, since the lower the degree of crystallinity the higher the transparency, highly crystalline PLA has poor optical properties.

Mechanical Properties

PLA has good mechanical properties, performing well compared to standard thermoplastics. It has low impact strength, comparable to non-plasticised PVC. The hardness, stiffness, impact strength and elasticity of PLA, important for applications such as beverage flasks, are similar to values for PET. Oriented PLA film can hold a crease or fold or retain a twist, properties inherent to paper and foil but usually lacking in plastic films. These properties, in combination with PLA's high flexular modulus and high clarity, are comparable with those of cellophane films (Gruber and O'Brien, 2002).

Thermal Properties

PLA has a relatively low glass transition temperature (~ 60 °C) and degrades quickly above this temperature in high moisture conditions. Due to its low Vicat softening point, PLA is less not suitable for filling at elevated temperatures (similarly to PET). PLA's low softening point also poses a problem for warehousing of products and use in automobiles. On the other hand, PLA's low heat deflection temperature (HDT) and high heat seal strength lead to good performance in film sealing. According to Cargill Dow, the melting point for PLA ranges from 120-170 °C; however, Treofan quotes a much lower figure of 85 °C (Treofan, 2003).

Other properties

PLA has high odour and flavour barrier. It also has high resistance to grease and oil, thus finding application in the packaging of viscous oily liquids. It is also suitable for packaging of dry products and short shelf-life products. It is not suitable for the packaging of carbonated beverages and other liquids due to its poor O_2-, CO_2- and water barrier. In comparison to starch polymers, PLA is superior in terms of moisture barrier, whereas the gas barrier is inferior (Petersen et al., 1999). In comparison to PP, PLA pellets are much more hygroscopic (water-absorbing) and therefore must be handled carefully. PLA foils, however, are not hygroscopic (Treofan, 2003). The low water barrier can be of interest for some applications; e.g. in clothing where high water transmission (high wick) for fabrics (Gruber and O'Brien, 2002) is a desirable property. The hydrolytic stability conditions close to some laundering, dyeing and finishing processes are borderline (Woodings, 2000). As for polyesters in general, PLA exhibits good chemical resistance to aliphatic molecules such as mineral oils and turpenes. The resistance to solvents, acids and bases is average to poor. Having a linear aliphatic structure, PLA has good UV resistance. This is in contrast to aromatic polymers such as PET, which are highly sensitive to UV. Since PLA is a polar material it has a high critical surface energy and is thus easy to print, metallise and dye. Its printability is similar to PET and better than PE and PP (Hycail, 2003). It is possible to print PLA using natural dyes and pigments which are heavy metal free and thus eligible for the DIN norm compostable logo. PLA is largely resistant to attack by microorganisms in soil or sewage under ambient conditions. The polymer must first be hydrolysed at elevated temperatures (>58 °C) to reduce the molecular weight before biodegradation can commence. Thus, PLA will not degrade in a typical garden compost. Under typical use and storage conditions PLA is quite stable. Additives which retard hydrolysis may be used for further stabilization (Brandrup, 1999)

Properties of copolymers, blends and composites

Copolymers (such as PLA/PCL) and blends (such as PLA/PHA, PLA/starch) have improved performance with respect to degradation rate, permeability characteristics, and thermal and mechanical properties. Overall processability is thus improved and the range of possible applications for PLA is broadened. Blends of PLA and natural fibres have increased durability and heat resistance and a lower cost to weight ratio compared to unblended PLA.

2.2.3 Technical substitution potential

Table 2-9 shows the substitution potential for PLA, according to interviewed representatives from three companies; namely one bulk producer - Cargill Dow (2003), one potential bulk producer – Hycail (2003), a joint venture between Dairy Farmers of America and the University of Groningen, currently looking into the feasibility of EU-based bulk production of PLA and one small volume/specialty producer – the German company Biomer (2003b). The two companies interested in the bulk market agree on the potential for PLA to partially replace **PMMA, PA and PET,** as well as seeing possibilities for PLA to substitute for **PP**. No possibility is seen for substitution for PC, POM and non-polymeric materials. There was no clear consensus on the other polymers.

Little or no substitution potential exists for PVC, PC and POM. **PVC** is already dying out in packaging uses, although it is used in building, construction and electrical. **PC**, with its high toughness coupled with transparency, and a very high Vicat softening point (120 ºC), holds 65% of the market for transparent plastics. At a price of € 2.5 per kg, it has entered the commodity market. There is thus very little prospect for PLA to compete. **POM** has extreme abrasion resistance for moving parts. PLA compares favourably to **PE/HD & LD** in terms of its aroma barrier and grease resistance; also it is stiffer, has a higher modulus, but is more expensive. PLA compares unfavourably in terms of it water barrier. A reasonable amount of substitution seems possible. In the nonwovens sector, PLA should replace PE (also PP) to some extent. Compared to PLA, **PP** has a high fatigue modulus so it is, for example, superior for hinges on packaging. It also has good heat resistance. Still. limited substitution is possible. PLA thin film (foil) could also replace PP in come applications. Compared to **PS crystal clear**, PLA is less transparent while elongation & breakage are comparable. **PMMA** has super clarity and transparency combined with good weatherability – important features in some applications which PLA cannot match. PLA has low abrasion resistance compared to **PA**, which is also fibrous and highly crystalline. This limits substitution possibilities. There are also interesting possibilities for substitution in fibre applications. Compared to PLA, **PET** has better printability and better barrier properties for packaging. In particular, PLA is a poor barrier for water; however this is in some respects a useful quality for packaging, e.g. for fog-free packaging of warm bread. PLA does not reach the heat and impact resistance of PET, but the heat resistance is still reasonable. The melting point of PLA is too low for it to challenge aromatic polyesters in mainstream textiles; however PLA can be easily blended with PET. When costs for PLA and PET reach parity, at least partial substitution in fibres and packaging should take place. **PBT** is highly crystalline and is used in automotive electrical applications. No substitution for PLA is possible. **PUR** foam has flammability requirements so PLA is a problem in this respect. **HI-PS** is very tough so only impact-modified PLA could compete. **ABS** is also very tough. Comparable impact strength for PLA can be achieved with an engineered blend. According to PLA foil producer Treophan (2003), PLA foil can replace **cellophane** in some applications.

Non-polymeric materials for which some substitution may be possible include wood and leather (e.g. for clothing), but quantities will not be significant.

Table 2-9: Technical substitution potential for PLA according to interviews with experts from Cargill Dow, Hycail and Biomer.
++ *full substitution* + *partial substitution* - *no substitution*

	PVC	PE-HD	PE-LD	PP	CC-PS	PMMA	PA	PET	PBT	PC	POM	PUR	HI-PS	ABS	non-poly
Cargill Dow	-	+	+	+	-	-/+	+	+	-	-	-	-/+	-	-	-
Hycail	+	-	-	+	+	+	+	+	+	-	-	-	+	+	-
Biomer	-	-	-	-	++	-	-	-	-	-	-	-	-	+	-

CC-PS: crystal clear polystyrene; HI-PS: high impact PS

2.2.4 Applications today and tomorrow

Producers report that potential PLA customers are starting to come forward at conferences and trade shows, indicating that PLA is gaining market acceptance (Hycail, 2003). In some cases, companies are interested in the possibilities for direct substitution of PLA for other mainly polymeric materials, while others are interested in exploiting certain unique properties, e.g. impact strength.

In Table 2-10, interviewed company representatives estimated the current and future market share of PLA in different sectors and commented on potential applications, barriers and experiences in relation to the range of possible PLA applications. Cargill Dow as the primary bulk producer estimates that 70% of PLA produced today is used in packaging. Hycail quotes a similar figure. Cargill Dow predicts a major shift away from packaging and towards fibres and fabrics, transportation and electronics. Hycail does not expect any major shifts in the use structure of PLA compared to the current situation. Notes pertaining to specific applications follow.

Table 2-10: Main applications for PLA – share of interviewed companies'[1,2] total production by market sector (scope: EU 15)

Sector	% of total production today		% of total production in 2020	
	Cargill Dow	Hycail	Cargill Dow	Hycail
Packaging	70 %	70 %	20 %	55 %
Building				
Agriculture	1 %	12 %		6 %
Transportation			20 %	2 %
Furniture				
Electric appliances and electronics (E&E)	1 %	1 %	10 %	10 %
Houseware		12 %		6 %
Other (fibres and fabrics)	28 %	3-5 %	50 %	21 %
Other (analytics)				
Total	100 %	100 %	100 %	100 %

[1] Cargill Dow (2003),

[2] Hycail (2003)

According to Petersen et al. (1999), if prices of approximately €2.00 per kg can be reached and adequate barrier properties can be met, PLA's potential for food **packaging** applications is very high due to its transparency, good mechanical properties and suitable moisture permeability for packaging of foods such as bread. Compared to starch (which has a moisture barrier too low for many applications), PLA has a better moisture barrier. For liquids such as juice or milk the volume must be accurate during the shelf life and in this respect PLA's water barrier is not adequate. Production of a flexible, water-resistant film, understood to be via a process of vapour deposition with alumina (Treofan, 2003), has been demonstrated; however this process adds about €1.00 per kg to the cost. PLA's good performance for packaging fats and oils is reported in interim results of the project Biopack: Proactive Bio-based Cheese Packaging (Biopack, 2003). It should be noted here that consumers in Germany expect a 4 colour print on cheese foil packaging, which is possible using biodegradable metal oxides but results in very 'colourful' compost (Treofan, 2003).

Examples of non-food applications include Panasonic's use of PLA for rigid transparent packaging of batteries with printed PLA film on the back side. Another possible application is windows for envelopes. According to Treofan (2003), since PLA is electrostatic an anti-static additive is required in this application and this has not yet been found. Somewhat contradicting this information is the reported preferential use of envelopes with PLA windows by Japanese government utilities (BPS, 2003). Perfume packaging could be an interesting market, since PLA is alcohol-resistant (Treofan, 2003). For detergents packaging, stress cracking resistance is a problem but this possibly could be overcome by using impact modified PLA.

The potential for PLA and PLA/fibre blends to be used in **building** applications will depend on issues such as adequate performance over a 20 year lifetime and price competitiveness.

Potential applications in **agriculture** include incorporation of a timed-release fertiliser in PLA sheet or molded forms and biodegradable plant clips. PLA is considered too expensive for mulch film. Also, degradation of mulching foils should occur at 25 ºC, whereas PLA requires a professional composting process that reaches 60 ºC.

In the **transport** sector, Toyota is currently developing applications for PLA blends and fibres in automobile interiors, including head liners, upholstery and possibly trimmings (e.g. around radios; see also Section 2.2.5) (Cargill Dow, 2003). Toyota is using a composite of kenaf fibre and PLA for moulded parts (e.g. spare tyre cover) and is also investigating nanocomposites of PLA with montmorillonite clay, which have been found to exhibit improved temperature resistance. PLA should be suitable for rugs and carpets and niche applications such as highly crystalline parts and injection-molded items but will prove a problem in many other applications (Hycail, 2003). There is no possibility to use it for external parts. The easy blending of PLA with PET may prove useful in the case of transport-related and other durables.

In the **electronics** sector, Fujistsu is making injection molded computer keys. Sony has produced a walkman with 85% PLA and 15% aliphatics (injection moulded) (Cargill Dow, 2003). Applications may be slow to develop since electronics is a highly regulated area, especially for high voltage applications (there are different test requirements for flammability, short-circuit testing etc.).

In another interesting application, a subsidiary of Sanyo Electric Co., Ltd in Japan recently announced the development of the world's first commercially viable compact disc to be manufactured from corn-derived PLA (NEAsiaOnline, 2003). The company worked jointly with Mitsui Chemicals Inc to develop the PLA until it had plastic properties that enabled it to be used for making discs. A single disc requires around 85 grains of a corn, so one head of corn could, in theory, be used to produce 10 discs. The firm plans to start accepting orders in December 2003 and hopes to be producing 5 million CDs in 2005. The plastic cases and film wrappers for the CD will also be made of natural materials. The discs take 50-100 years to degrade. The projected price is 3 times that of a normal plastic disc, but this is expected to be reduced to 1.2 times as the discs become more popular (Tech, 2003).

One recent development which should enable wider application of PLA in electronics products is NEC Corporation's process for imparting flame resistance to PLA without the use of halogen or phosphorous compounds that are toxic when burned. NEC's PLA product has passed top-level flame resistance standards. The product is reported to have heat resistance, mouldability and strength comparable to fibre-reinforced polycarbonate used in desktop-type electronic products (Greenbiz, 2004).

PLA fibre has potential in the **furniture** sector in applications in which flame resistance is important, such as hospitality, industry and home furnishings (Cargill Dow, 2004). . Exploring applications in the **houseware** sector, Interface Inc. is working with Cargill Dow on development of carpets. There is a possible small volume market for cutlery and plates.

Other promising applications include fibres and nonwovens, where garments made from 100% PLA or blends of PLA with wool and cotton are comparable and in some respects superior to the well-established PET blends (Gruber and O'Brien, 2002. Also under discussion is the concept of high melting PLA/lyocell (regenerated cellulose) blends replacing the extremely successful blend of polyester/cotton (Woodings, 2002).

2.2.5 Current and emerging producers

Following the establishment in 2000 of the joint venture **Cargill Dow** (see Chapter 2.2), in late 2001, Cargill Dow commenced large-scale production of PLA at a plant with design capacity 140,000 t.p.a. located in Blair, Nebraska, USA. The scheduled production was 70,000 t in 2002 and 100,000 t in 2003 is (the actual production is unknown, see also end of Section 3.4). The plant is currently ramping up to full production[7]; with operation at capacity planned for 2004 (Cargill Dow, 2003). In October 2002, Cargill Dow started up a new lactic acid production facility, based on own technology. This will lead to reductions in manufacturing costs over the longer term for feedstock requirement (180,000 t.p.a. of lactic acid) (Cargill Dow, 2003).

Cargill Dow has about 250 persons employed in PLA-related activities part-time. Total capital investment to date amounts to US $300 million in plant and US $450 million in R&D, process development and technical support together.

Cargill Dow has business development collaborations with numerous customers from North America, Europe, Asia and Japan. In Europe, Cargill Dow has issued two licenses for PLA foil: one to Bimo in Italy (simultaneous stretching process) and one to the Treofan Group of Trespaphan GmbH (two stage stretching process) (Treofan, 2003). While Bimo has stopped the use of PLA because of difficulties in the process, Treofan (which has a 200 000 t.p.a. business in polypropylene foil) has been selling PLA foil under the brand name Biophan since mid-2001.

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[7] Based on interviews with PLA producers and converters, it is estimated that production in 2002 was about 30,000 tonnes (own estimate).

Cargill Dow's expansion plans are for two additional PLA plants of a similar capacity to the first, to be built wherever the market develops and in combination with best manufacturing economics (Cargill Dow, 2003). The combined production capacity will be 500,000 t.p.a. Both these new facilities should be in operation by 2010.

For its current process, Cargill Dow uses corn (maize) as the feedstock due to its low price and wide availability in the U.S and its high starch content. The second plant will also use a crop as feedstock: (maize, cassava or rice depending on location; sugar beets could be an option for Europe but are probably too expensive). Within the ten-year time frame planned for construction of a third plant, Cargill Dow intends to be using cheap biomass as the primary feedstock, e.g. lignocellulosics from corn stover. In the future (before 2010) the company expects to further improve PLA's sustainability profile by deriving its process energy from biomass originating partly from the process feedstock (e.g. corn stover) and partly from wind energy (Cargill Dow, 2003).

Cargill Dow has won several award for its NatureWorks® PLA technology, including in the US Department of Energy's Office of Industrial Technologies (OIT) Technology-of-the-Year award (2001) for a technology that demonstrates the potential for improved energy efficiency along with economic and environmental benefits (Ewire, 2001); and the Presidential Green Chemistry Challenge, Alternative Reaction Conditions Award, for the development of a revolutionary process to make plastic from corn (Ewire, 2002).

Hycail BV, a spin off from the University of Groningen, was set up in 1997 to investigate the production of PLA from lactose in whey permeate, a by-product of cheese manufacture. In 1998 Dairy Farmers of America (DFA), interested in adding value to whey permeate from their numerous cheese factories, gained shares in Hycail. In April 2004, Hycail will operate semi-commercial pilot plant producing 1000 t.p.a. of high molecular weight PLA (Hycail®HM) for pellets, film and bags and 10-20 t.p.a. of low molecular weight PLA for hot-melt adhesives and the like. A laboratory and small pilot plant have been operating since 1995 (Hycail 2003a).

Hycail's goal is an integrated facility for lactic acid, with lactic acid being produced by another company in a partnership agreement and PLA being produced by Hycail. By the end of 2003, the companies expect to have a clear idea of the manufacturing cost of lactic acid production from whey permeate lactose and other sugar sources. A suitable process for scale-up of integrated PLA manufacture has already been identified and a Freedom to Operate opinion has been received. Hycail plans to have the semi-commercial plant in the Netherlands running in March 2004 and to commence construction of a full-scale plant with capacity between 50,000t.p.a. and 100,000 t.p.a. in 2005 and to start up by the end of 2006. A second plant should follow by 2010.

Hycail has not yet decided where the first full-scale plant will be located. The preference is for the Netherlands; but it could be elsewhere in the EU depending on the availability of subsidies, permissions regarding partnership operations and cheap sugar sources.

Biomer, a biotechnology company located in Kráilling, Germany has recently begun producing PLA on a small-scale commercial basis. The product is sold to converters for the production of transparent packaging films and other specialty injection moulding and extrusion applications. Biomer has also been producing the bio-based polymer poly(3-hydroxybutyrate) P(3HB) (see Section 2.4) since 1994-5. No plans are known in relation to upscaling.

Within the **European Union,** other companies with an interest in large volume production of PLA include the Belgian company **Galactic**, a producer of lactic acid and lactic acid derivatives. Its subsidiary Brussels Biotech is involved in R&D activities for PLA for industrial applications such as food packaging, non-woven products and disposables (Galactic Laboratories, 2003).

Inventa-Fischer GmbH is offering turn-key plants with a capacity of 3,000 t.p.a. (Hagen, 2000). In the year 2000 Inventa-Fischer GmbH & Co KG has developed the process which promised to reduce the cost price of Polylactide close to other engineering plastics or fibre materials. The basic engineering for a pilot plant was supported by the German Federal ministry of Agriculture (Inventa Fischer, 2000). It was one of the targets of the project to create new sales prospects in the non-food market to the German farmers which suffer from enforced disuse of agriculture areas. Rye was selected as the raw material, because of the poor soil quality in the concerned areas. With some modification the process is able to convert wheat or maize in the same way. The plant will demonstrate the complete process from rye up to the polylactide chips in the pilot scale. The future producer of PLA shall be independent from price, quality and availability of intermediate products like lactic acid. The technological highlight is the continuous fermentation. Continuous operation reduces the number and the size of required equipment. In the polymerisation process Inventa-Fischer applies reactors and equipment which are proven for similar polymers at large-scale industrial production plants. Therefore, scale –up from the pilot plant to an industrial scale plant can be made with high reliability.

During the basic engineering of the 3,000 t.p.a. pilot plant also the cost price of the polylactide could be calculated. The individual costs of all required plant components including piping, process control, and construction have been summed as well as costs of services like engineering, design, handling, erection and start-up. Only building site cost was not included. Fixed costs have been calculated considering depreciation, interest and insurance. Raw and auxiliary materials together with energy and wearing parts like membranes make up the main part of the specific cost of PLA. Adding costs of labour, repair and maintenance a cost price of PLA of 2.20 €/kg resulted. Although there have been many interested potential producers, no plant has been realised. At present Inventa Fischer is in negotiation with a client outside Europe (Inventa Fischer, 2003).

The German company food packaging company **Apack** holds a license for PLA technology originally developed by Neste Chemicals, now the property of Fortum Ojy, Finland (Södergård and Stolt, 2002)[8]. The Italian Engineering company **Snamprogetti** is reported to have developed a plant with a capacity of 2,500 t.p.a. for food/polymer grade PLA by the fermentation of hydrolyzed starch in China. The plant should be producing polylactates since mid 2003 (ENI, 2001).

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[8] BP is looking into methane-derived lactic acid; however it is expected to be at a disadvantage due to the petrochemical basis of production. Methane-derived lactic acid could also be formed from purified biogas as renewable carbon source; however further examination of this is outside the scope of this study.

In Japan, **Mitsui Chemicals** produces PLA via the direct polycondensation route and has been engaged in semi-commercial production (500 t.p.a.) since 1996 (product name: LACEA). **Shimadzu Corporation** formerly produced small commercial quantities of PLA via the ROP route (several hundred t.p.a. in 1997) but has since ceased production. In the mean time, **Toyota** has purchased Shimadzu's PLA technology (Cargill Dow, 2003). Toyota is building a 1000 t.p.a. PLA pilot plant within an existing TMC production facility in Japan. Using sugarcane as the base material, TMC intends to carry out the entire process from fermenting and purifying the lactic acid to polymerization of PLA. The pilot plant, scheduled for startup in 2004, will be used to investigate the feasibility of reaching mass production cost and quality targets (TMC, 2003a).

Aside from this development work, Toyota is already using a composite of PLA and kenaf (East Indian Hibiscus) under the name 'Toyota Eco-Plastic' for the spare tyre cover; and PLA fibre for the floor mats in the new Raum, which was launched on the Japanese market in May 2003 (TMC, 2003).

2.2.6 Expected developments in cost structure and selling price

Selling price

Cargill Dow, currently the only large volume producer of PLA, sells samples at €3.40 per kg and supplies large volume customers (such as Treofan in the EU) at a price of **€2.20** per kg (Cargill Dow, 2003). The latter price is set at a level at which PLA is able to compete with a limited number of engineering polymers Cargill Dow views PLA as a specialty polymer moving toward commodity polymer prices. By way of comparison, the price of PLA foil is €5.50 - €6.00 per kg; cellophane is in the same price range; while PP foil is about one third of the price at €1.50 - €2.50 per kg (Treofan, 2003). According to an internal study by Treofan, a tenfold increase in production of PLA foil would result in a halving of the price (to €3.00 per kg).

Cost structure

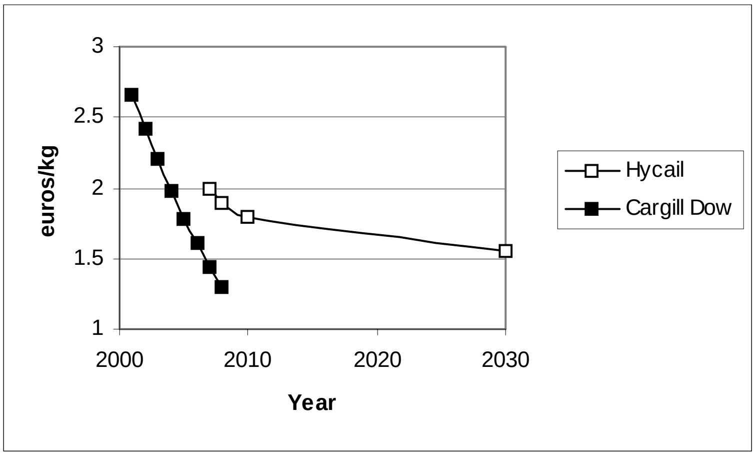
The final cost of producing PLA depends primarily on the efficiency of the initial fermentation process to produce the lactic acid monomer (Petersen, 1999). Lactic acid currently comprises around 40 to 50% of Cargill Dow's total costs. According to Cargill Dow (2003), for true competitive status of PLA on the engineering polymers market, the cost of lactic acid should decrease to a level on par with the price of ethylene.

For Hycail the share of lactic acid to total costs is much higher at 60 to 65%, of which an estimated 40% is due to the production of lactate salt and 60% to acidulation and purification to polymer grade lactic acid (Hycail, 2003). It must be noted that this is for pilot plant scale, with externally sourced lactic acid. By 2006-7, in partnership with the lactic acid producer and almost certainly using whey permeate, Hycail will bring this cost down to 25% (by 2006-7). World class cost structure will be achieved by Hycail due to implementation of breakthrough lactic acid technology with its partner, use of whey permeate and other "waste" sugar sources and novel conversion technology in its PLA plant as compared to state of the art.

Expected price developments

Figure 2-6 shows the expected market price for PLA up until the year 2010, interpreted from Cargill Dow and Hycail pricing targets. Hycail also suggests a price in the year 2030. Cargill Dow's goal is to decrease the selling price to be competitive with PET on a density adjusted basis as soon as possible (Cargill Dow, 2003). After 2010, the use of renewable energy and alternative biomass feedstocks is expected to generate further improvements in price competitiveness. Hycail's predictions are more conservative (€2.00 per kg in 2007, €1.80 per kg in 2010, €1.50 - €1.60 per kg in 2030), in line with expected higher costs for lactic acid within the same time frame. Hycail believes that it will be very hard to compete with PET from a cost point of view, even within a time frame of 2030. However, Hycail is also of the opinion that for a fully integrated lactic acid/PLA plant with production capacity in the range of 200,000-300,000 t.p.a., a selling price of €1.20 - 1.30 per kg is achievable.

Figure 2-6: Producer price estimates for PLA - 2010 and beyond



2.2.7 Environmental impacts

Publicly available life cycle assessment data for polylactides are scarce. Cargill Dow has published cradle-to-factory gate energy and CO_2 data for PLA from corn (Vink et al., 2003). As shown in Table 2-11 *total* fossil energy requirements of PLA are clearly below the respective values for the petrochemical polymers while the *process* energy requirements are higher for the first commercial PLA plant (termed PLA-Year 1 in Table 2-11). Further energy savings are expected to be achievable by optimization of the lactic acid production technology (see row "PLA - Year 1, optimized") and – more importantly - by using lignocellulosic feedstocks (corn stover) as additional source for fermentable sugars in combination with energy production from the lignin fraction (Table 2-11, row "PLA – Biorefinery"; Vink et al., 2003). The estimated cradle-to-factory gate energy requirements for PLA production from rye and from whey in Table 2-12 show that also small plants (3 kt p.a. and 4.2 kt p.a. respectively) may be rather energy efficient (the expected values remain to be proven in commercial plants). The use of a waste product like whey (Table 2-12) may allow savings up to 35% compared to production from cultivated crops (rye or corn).

Table 2-11: Cradle-to-factory gate energy requirements and CO_2 emissions for Cargill Dow's PLA as compared to petrochemical polymers (Vink et al., 2003; personal communication, Vink, 2003)

	Process energy, fossil [GJ/t plastic]1)	Feedstock energy, fossil [GJ/t plastic]	Total fossil energy [GJ/t plastic]1)	Energy and process related GHG emissions [kg $CO_{2,eq.}$/t plastic]2)	CO_2 absorption, plant growth [kg CO_2/t plastic]3)	Net GHG emissions [kg CO_2,eq./t PLA]1)
PLA - Year 1	54.1	0	54.1	3990	-2190	1800
PLA - Year 1, optimised	48.8	0	48.8	3390	-2190	1200
PLA - Biorefinery	29.2	0	29.2	1890	-2190	-300
HDPE4)	31	49	80	1700	0	1700
PET (bottle grade)4)	38	39	77	4300	0	4300
Nylon 6 4)	81	39	120	5500	0	5500

1) Data from Vink et al. (2003)

2) Emissions for PLA taken into account in this column are mainly CO_2 from energy use; other emissions included are methane and nitrous oxide from fertilizer use. Values for PLA in this column have been determined by deducting from the net GHG emissions (first column from the right) the quantities of CO_2 absorbed during plant growth (second column from the right).

3) Personal communication with E. Vink, Cargill Dow, 2002. Note that data in this column refer to kg CO_2 and not kg $CO_{2,eq}$.

4) Data for petrochemical polymers from Boustead (1999/2000).

Table 2-12: Estimated cradle-to-factory gate energy requirements for PLA production from rye and from whey

	Total energy (non-renewable) in GJ/t PLA	
	from rye*)	from whey**)
Cultivation	8.7	0.0
Milling	6.6	0.0
Transportation	0.0	2.3
Hydrolysis and fermentation	33.9	25.0
Polymerisation	12.8	12.8
Total	62.1	40.1

*) Data for a 3 kt p.a. PLA plant; estimated on the basis of personal communication with R. Hagen, Inventa Fischer, 2002.

**) Data for a 4.2 kt p.a. lactic acid plant acc. to Börgardts et al., Fraunhofer-IGB (1998).

2.3 Other polyesters from potentially bio-based monomers

Apart from polylactic acid (PLA) which as described in the preceding section is well advanced in terms of reaching large-scale production, a number of other polyesters have the potential to be produced from a bio-based feedstock. The most important of these are shown in Table 2-13, together with trade names for each and the constituent monomers. In all cases, the polymer is produced from a diol and one or more dicarboboxylic acids (diacid). The diol in this scheme is bio-based (PDO or BDO), while the diacid is either bio-based (succinic or adipic acid) or petrochemical-based (PTA or DMT). One of these polyesters, PTT, is on the verge of being produced from a bio-based monomer (PDO) on a commercial scale and there is a reasonable likelihood that another, PBS, will soon be produced from bio-based succinic acid. The status of the other polymers in the table with respect to bioroutes is unclear. In this section it has been decided to take as case studies the first three polymers in Table 2-13, namely PTT, PBT and PBS, with the assumption that learnings will be applicable to others not explicitly discussed.

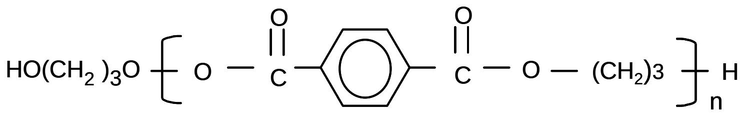
Table 2-13: Polyesters from a (potentially) bio-based monomer

Polymer		Monomer			Monomer
Chemical Name	Trade Name(s)	Potentially bio-based			petrochemical
Poly(trimethylene terephthalate) PTT	Sorona^{TM} **Corterra®**	**PDO**			**PTA/DMT**
Poly(butylene terephthalate) PBT	**various**	**BDO**			**PTA/DMT**
Poly(butylene succinate) PBS	**Bionolle 1000®**	**BDO**	**succinic acid**		
Poly(butylene succinate adipate) PBSA	Bionolle 3000®	BDO	succinic acid	adipic acid	
Poly(butylenesuccinate terephthalate) PBST	Biomax® Eastar Bio®	BDO	succinic acid		PTA/DMT
Poly(butyleneadipate terephthalate) PBAT	Ecoflex®	BDO		adipic acid	PTA/DMT

2.3.1 PTT from bio-based PDO

Poly(trimethylene terephthalate) (PTT, Figure 2-7) is an linear aromatic polyester produced by polycondensation of 1,3-propanediol (trimethylene glycol or PDO) with either purified terephthalic acid (PTA) or dimethyl terephthalate (DMT) (Brown et al., 2000). While both these monomers – the diacid and the diol component - are conventionally derived from petrochemical feedstocks, DuPont, Tate & Lyle and Genencor have recently succeeded in producing PDO using a aerobic bioprocess with glucose from corn starch as the feedstock (DuPont, 2003), opening the way for bulk production of PTT from a bio-based monomer. Apart from PTT other acronyms are PTMT (also for polytrimethylene terephthalate) and PPT (for polypropylene terephthalate).

Figure 2-7: PTT molecule



As an engineering thermoplastic, PTT has a very desirable property set, combining the rigidity, strength and heat resistance of poly(ethylene terephthalate) (PET) with the good processability of the poly(butylene terephthalate) (PBT). PTT may be used to produce fibres for carpets and industrial textiles where it has the good resiliency and wearability of nylon, combined with the dyeability, static resistance and chemical resistance of PET. As a spunbond fibre for apparel, its property set includes good stretch recovery, softness and dyeability. When blended with other resins it can improve strength, flexibility, and barrier properties in moulding and extrusion applications (DuPont, 2003).

PTT was first synthesised in 1941. In the late 1960s, Shell attempted commercialisation but was unsuccessful due to the high cost of one of the starting materials, namely PDO produced via hydration of acrolein. Thus, while PET and PBT became very successful commercial polymers, PTT, despite its good physical and chemical properties and numerous potential applications, was not commercialised. It was not until the 1990s that commercialisation of PTT was revisited. This time Shell used the more cost effective process of continuous hydroformylation of ethylene oxide with newly-developed catalysts. Commercialisation of PTT under the brand name Corterra® followed in 1999. Shell, in joint venture with SGF Chemie JV, started construction of the first world-scale PTT plant in Montreal, Canada. The plant is scheduled for completion in 2004 (Shell, 2003) and has a capacity of 86,000 t.p.a. of PTT at a project cost of € 40 million (Textile World, 2002).

In parallel to the commercialisation efforts of Shell, DuPont has introduced its own product from PTT (also know as "3GT" [9]), Sorona™. Whereas Shell's focus for Corterra® is on industrial fibres and engineering plastics, DuPont is specifically targeting the high-value apparel market for its Sorona ™ fibre. DuPont currently also produces PDO from petrochemicals (using Degussa technology for hydration of acrolein) but has firm plans to make the transition to bio-based PDO by 2005. Whereas Shell concluded that the biotechnological route to PDO (at the time, via fermentation of glycerol) was unattractive (Chuah, 1999), DuPont continued research in collaboration with Genencor into metabolic engineering of an organism capable of directly producing PDO from glucose at acceptable yields and rates. In early 2003 DuPont announced that a commercially viable process had been attained (DuPont, 2003a) and that bio-based PDO would soon become the platform chemical for its PTT process. DuPont's bioprocess to PDO was awarded the U.S. Environmental Protection Agency's Presidential Green Chemistry award in early 2003 (NREL, 2003).

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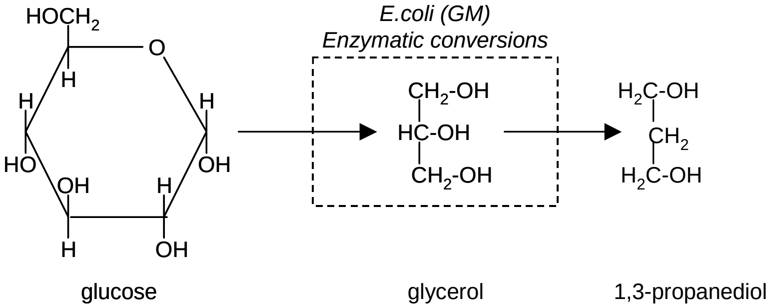
[9] DuPont has coined the term "3GT" as the generic name for the family of copolymers of PDO ("3G") and terephthalic acid ("T"). By extension, the generic name "4GT" refers to the family of copolymers of BDO (1,4-butanediol or "4G") and terephthalic acid ("T") more generally referred to as PBT.

2.3.1.1 Production

The natural fermentation pathway to PDO involves two steps: yeast first ferments glucose to glycerol, then bacteria ferment this to PDO. In the bioprocess developed by DuPont, dextrose derived from wet-milled corn is metabolised by genetically engineered *E. coli*[10] bacteria and converted within the organism directly to PDO via an aerobic respiration pathway (Figure 2-8)[11]. The PDO is then separated from the fermentation broth by filtration, and concentrated by evaporation, followed by purification by distillation. The PDO is then fed to the polymerisation plant.

Figure 2-8: Bioroute to PDO



PTT can be produced either by transesterification of dimethyl terephthalate (DMT) with PDO, or by the esterification route, starting with purified terephthalic acid (PTA) and PDO (Figure 2-9). The polymerisation can be a continuous process and is similar to the production of PET (Thiele, 2001). In the first stage of polymerisation, low molecular weight polyester is produced in the presence of excess PDO, with water of esterification (in the case of PTA) or methanol (in the case of DMT) being removed. In the second stage, polycondensation, chain growth occurs by removal of PDO and remaining water/methanol. As chain termination can occur at any time (due to the presence of a monofunctional acid or hydroxyl compound), both monomers must be very pure. As the reaction proceeds, removal of traces of PDO becomes increasingly difficult. This is compensated for by having a series of reactors operating under progressively higher temperatures and lower pressures. In a final step, the highly viscous molten polymer is blended with additives in a static mixer and then pelletized.

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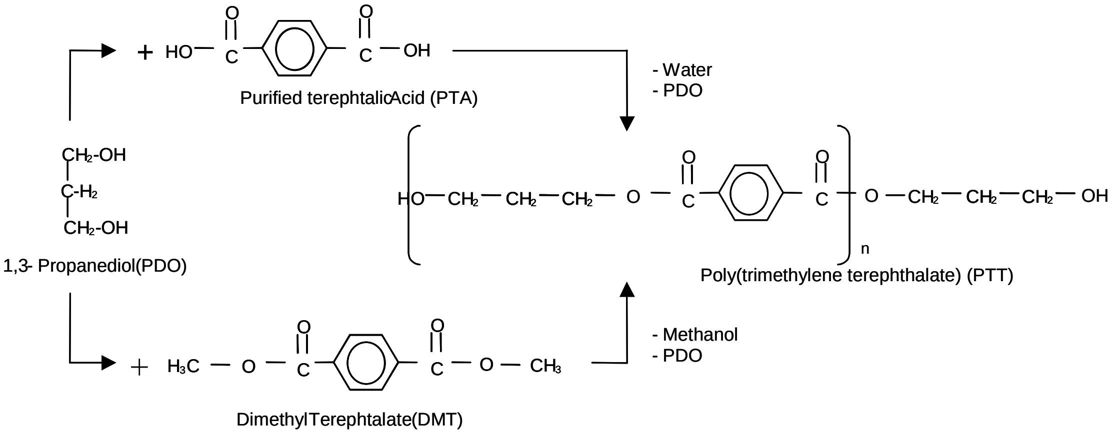
[10] The *E. coli*, which has 26 gene modifications (Visser de, 2003), was developed by Genencor International and DuPont is said to have a 500-fold increase in bioprocessing productivity, compared to the microorganisms whose genes were extracted and incorporated into the modified bacteria (Dechema, 2003).

[11] It is understood that the microorganism currently produces PDO via an anaerobic pathway but DuPont is also looking into an aerobic pathway since this has a higher theoretical yield; as well as increasing the size of a theoretical production facility from 25,000 to about 50,000 tonnnes/year of PDO (Morgan, 1998).

Since PTT production is analogous in many ways to that of PET, it is possible in general with some modifications to convert existing PET facilities (primarily, batch plants) to PTT production. The PDO unit needs to be built separately. The cost for conversion of a PET facility to PTT is between 10% to 20% of the cost of building a new plant (Norberg, 2003), equating to relatively low startup capital. This also means that there is the possibility of a reasonably fast increase in global production volumes over the next few years should PTT prove attractive to current PET producers. Of the two main players, the approach DuPont has taken is to modify existing PET facilities; while Shell is constructing an entirely new facility for PTT.

Figure 2-9: Production of PTT from PDO and PTA or DMT



Other products from bio-based PDO

In the future, it is likely that DuPont will also use PDO in the development of engineering polymers similar to PBT and high performance elastomers such as copolyester ethers (COPE). PDO could also be used as a chain extender for thermoplastic polyurethanes instead of 1,4-butanediol (Morgan, 1998).

2.3.1.2 Properties

PTT combines physical properties similar to PET (strength, stiffness, toughness and heat resistance) with processing properties of PBT (low melt and mould temperatures, rapid crystallisation, faster cycle time than PET) (Shell, 1997) as well as having similarities to polyamide (PA 6,6) and polypropylene (PP), for fibre applications and polycarbonate (PC) for moulding applications (Table 2-14). There is also some overlap in terms of properties and processability (fibres and films) with PLA and cellophane.

Chemical and physical properties

In general, PTT is similar in molecular weight and molecular weight distribution to other polyesters (Hwo and Shiffler, 2000). The polyester backbone is saturated and hence unreactive (Thiele, 2001). As for other linear polyesters it is crystalline, hard, strong and extremely tough. The density of PTT is slightly lower than PET and similar to PBT.

PTT has an odd number (three) of methylene units between each of the terephthalates whereas PBT and PET both have an even number of methylene units. The odd number of methylene units affects the physical and chemical structure of PTT, giving it elastic recovery beyond that of PBT and PET and into the range of nylon (Houck et al., 2001).

Mechanical and thermal properties

The tensile strength and flexular modulus decrease between PET, PTT and PBT respectively. The elongation to break of PTT staple (fibre) is significantly larger than either PET or nylon, suggesting improved tear strength. PTT's initial modulus which is lower than PET or nylon, corresponds to a less rigid and hence softer, more easily hydroentangled (nonwoven) fibre. PTT has a melting point 37°C and a glass transition roughly 25 °C lower than PET, thus requiring correspondingly lower processing temperatures (Hwo and Shiffler, 2000).

Other properties

PTT films have low vapour permeation. Due to the moderate glass transition temperature, PTT is dyeable with common dispersion dyes at atmospheric boil without a carrier. Its exhibits uniform dye uptake and with selected dyes, colourfastness comparable to nylon (Houck et al., 2001), and stain resistance. It also has excellent UV resistance (British Plastics, 2003) and low static-charge generation; hence its suitability for carpeting. PTT fibre has been found in consumer tests to have a softer feel than polyamide and PET, which is a desirable property for apparel.

Conversion technologies, blends and composites

Most interest and development activity relating to PTT lies in filament and fibre spinning (Thiele, 2001). PTT can be spun and drawn at high speeds, resulting in a fibre suitable for applications such as sportswear, activewear, and other specialty textiles. It can be processed on conventional equipment for PET, provided moisture content is kept below 30 ppm and provisions are made for the lower melt point and glass transition temperature compared to PET. Unlike PET, undrawn PTT rope will not harden when exposed to water at temperatures over 60-70 °C and therefore has potentially higher fibre quality (Hwo and Shiffler, 2000). Its heat-setting properties make PTT particularly useful in non-woven fabrics (Houck et al., 2001). Interest in developing PTT as an engineering plastic and for packaging technologies is expected to grow as standard resins become available on the market (Thiele, 2001).

There is good potential for PTT to be blended with other polymers, in particular PET and nylon. Chuah et al. (1995) report that PTT can be spun in a PTT/PET bicomponent (side by side) resulting in a crimp due to differential shrinkage that yields a high loft but retains other desirable traits. Core-sheath bicomponents are also being produced. PTT can also serve as a crystallization enhancer (due to its faster crystallisation) for PET within a lower range of addition (Thiele, 2001).

Table 2-14: Properties of polymers potentially from bio-based monomers and selected other polymers used in fibre or engineered thermoplastics applications[1]

Raw material basis	Potential bio-based monomer				Petchem-based			
Polymer name	Poly (trimethylene terephthalate)	Poly (butylene terephthalate)	Poly (butylene succinate)	Poly (amide)-6 (nylon-6)	Poly (ethylene terephthalate)	Poly (amide) -6,6 (nylon-6,6)	Poly (carbonate)	Poly (propylene)
Acronym	PTT	PBT	PBS	PA 6	PET	PA 6,6	PC	PP
Polymer structure	aromatic polyester	aromatic polyester	aliphatic polyester	polyamide	aromatic polyester	polyamide	polycarbonate	polyolefin
Physical properties								
Density (g/cm^3)	1.35	1.34	1.23	1.13	1.40	1.14	1.2	0.91
Haze[b] (%)				2-3[a]	2-5	2-3[a]		1-4
Mechanical properties								
Tensile strength at yield (MPa)	67.6	56.5	62	80	72.5	82.8, 90	65	28
Elongation at yield[c] (%)			710	50-100		20		500
Flexular modulus (MPa)	2760	2340	470	2410	3110	2830	2350	1690
Thermal properties								
Heat deflection temp (°C)	59	54	97	55-75	65	90	129	
Melting point (°C)	225	222-232	90-120	220	265	265		168
Glass transition temp (°C)	45-75	30-50	-45 to -10	40-87	80	50-90		-17 to -4

[1] Refs: Hwo & Shiffler (2000); Grothe (2000); Brandrup et al. (1999); Leaversuch (2002); Galactic (2003); Chuah (1999); Morgan (1998); Brydson (1989); Brandup (1989); Brikett (2003); Kubra Kunstoffen (2003); Kawashima et al. (2002); deKoning (2003); Plasticbottle Corp (2003); Thiele (2001); Showa HP (2003).

[a] Gen. fig. for nylons; [b]Biaxially oriented films; [c]ASTM D 882.

2.3.1.3 Technical substitution potential

Although no interviews were held with company representatives, it may be concluded from the property comparisons with other polymers that PTT's substitution potential (Table 2-15) is very high for nylon and PET, and moderately high for PBT, PC and PP. It is important to note that if the list of materials is extended to include bio-based polymers, PTT could substitute to some extent also for PLA in the market being established by Cargill Dow (especially in fibre applications), possibly also for PHA, and for cellophane film, depending on biodegradability requirements. The (theoretical) substitution potential of bio-based for petrochemical-based PTT is 100%, since the product should be identical assuming feedstock qualities and polymerisation processes are equivalent. In practice, as for all other polymer substitutions, the price will largely determine the actual extent to which substitution takes place.

Table 2-15: Technical substitution potential for PTT
++ *full substitution* + *partial substitution* - *no substitution*

	PVC	PE-HD	PE-LD	PP	CC-PS	PM-MA	PA	PET	PBT	PC	POM	PUR	HI-PS	ABS	non-poly
PTT	-	-	-	+	-	-	++	++	+	+	-		-	-	-

2.3.1.4 Applications today and tomorrow

Applications for PTT are being developed primarily in the fibres (textile, carpet, apparel) and packaging (films) sectors. While PET will continue to be preferred for carbonated beverage bottling, PTT is expected to substitute for PET to some extent in fibre applications as well as for various packaging films and other items such as (Thiele 2001) X-ray film, magnetic tape (audio, video and computer) metallized film, strapping and labels. Also novel applications for PTT are being developed, for example Solenium is a composite flooring material designed for institutional and hospital use that capitalises on PTT's elastic regain, durability and colourfastness properties (Houck et al., 2001).

Compared to other polymers discussed in this report, PTT is unique in that it is only just emerging on bulk markets, and before these markets are properly established it is expected that DuPont will fully substitute bio-based PTT for its current petrochemical-based PTT. In terms of the two key players, there seems to be a delineation between Shell's commercialisation interests and those of DuPont: Shell is mainly targeting the houseware (carpeting) sector for Corterra® and expects 20% of the material to go into typical engineering-type applications; e.g. moulded housings for appliances and electronics (Morgan, 1998). DuPont, on the other hand, is focusing its development efforts for Sorona ™ on fibres for apparel. It is thus expected that applications for PTT will be developed in parallel by both companies (and possibly other market entrants in the near future), with PTT broadening its application base and gaining market share over other polymers in the next few years. As discussed in the previous section, price competitiveness (along with possibly some influence from marketing strategies) will chiefly determine the extent to which bio-based PTT gains market share at the expense of petrochemical-based PTT.

2.3.1.5 Current and emerging producers

At present, DuPont is the only company known to be commercialising a bio-based route to PDO. DuPont's pilot facility for production of corn-derived PDO is located in Decatur, Illinois, where carbohydrate processor Tate & Lyle operates a corn wet mill (Genencor, 2003). DuPont and Tate & Lyle PLC have set up a 50/50 joint venture DuPont Tate & Lyle BioProducts, LLC which will be based in Wilmington, Delaware. The company plans to construct its initial commercial manufacturing plant adjacent to an existing facility in Loudon, Tenn., with startup scheduled for 2006. A pilot facility in Decatur, Illinois has been operating for several years (DuPont, 2004). DuPont's continuous polymerisation PTT plant, located in Kinston, NC, U.S., was built with an initial capacity of 9,800 t.p.a. (October 2000) and the capability to expand to 40,800 t.p.a. (Genencor, 2003). The Kinston plant has the capability to shift its production from petroleum-based to bio-based PDO (DuPont, 2003a).

In October 2003, The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and DuPont announced a US $7.7 million joint research agreement to collaboratively develop, build, and test a bio-refinery pilot process that will make value-added chemicals (including PDO) from the starch-containing kernels and electricity and fuel-grade ethanol from the corn stover. The agreement is part of the larger $38 million DuPont-led consortium known as the Integrated Corn-Based Bioproducts Refinery (ICBR) project. The ICBR project—which includes DuPont, NREL, Diversa Corporation, Michigan State, and Deere & Co.—was awarded US $19 million in matching funds from the Department of Energy last year to design and demonstrate the feasibility and practicality of alternative energy and renewable resource technology (NREL, 2003). As a bulk volume producer of chemicals and polymers, DuPont's involvement in these projects indicates that developments in bio-based routes are likely to be substantial in the coming years. Shell expects the demand for PTT to exceed 1 million t.p.a. in 2010 (Shell Chemicals, 2003).

2.3.1.6 Expected developments in cost structure and selling price

No costs are available for the DuPont process for PDO and PTT production; therefore cost estimates will be made based on available data.

Selling price

No market prices could be found for PTT. According to DuPont representatives, Sorona^{TM} will be priced at the same level as Nylon 6 (Franklin, 2002). The price of Nylon 6 is in the range of € 1.30 - € 1.40 per kg in Asia (Norberg, 2003) and € 1.50 - € 1.60 per kg in the US. From this one can roughly estimate a market entry price for PTT in the range of € 1.30 - € 1.60 (average € 1.45) depending on the location and market conditions at the time.

Cost structure

The cost of biotechnological production of 1,3-propanediol (PDO) by fermentation of glycerol found in BioMatNet (2003) was assessed to be € 1.77 per kg PDO; based on a plant capacity of 75000 t.p.a. The cost of PTA and DMT are € 0.60 and € 0.62 per kg respectively (TIG, 2001).

Taking the case of PTT from bio-based PDO (by fermentation) and PTA, the raw material costs are given in 2-16. The ratio is determined by the stoichiometry of the reaction. Other raw materials apart from the two main ingredients are neglected. The price of PDO is more than twice that of PTA; but since a relatively small amount of PDO is required to produce 1 kg of PTT, the overall contribution of PDO to feedstock cost is roughly only 60%. The total feedstock cost is estimated at € 1.14 per kg PTT. Assuming similar cost ratios as for the production of PLA (Section 2.2.6; costs due to lactic acid are in the range of 40-65% of total), one can estimate the total direct costs for producing PTT to be in the range of € 1.75 to € 2.85 (average € 2.30) per kg. This is significantly above the planned market price but could be feasible in the first phase of market development while learning effects at the company level are still being realised.

Table 2-16: Feedstocks costs for PTT production from PTA and PDO

Feedstock	Cost, €/kg	kg feedstock per kg PTT	Cost, €/kg PTT	% of feedstock costs
PDO	1.77	0.37	0.65	57
PTA	0.60	0.81	0.49	43
Total	-	-	1.14	100

Expected price developments

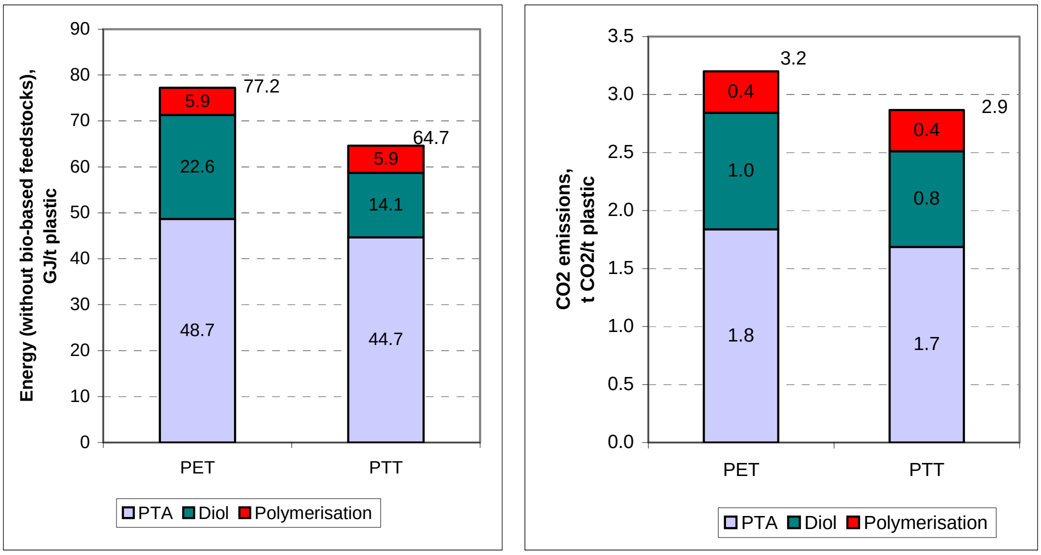
As previously noted, DuPont expects the market price of PTT to track the price of Nylon 6, with a slight premium being possible if (as claimed by DuPont) the superior attributes of PTT fibre over Nylon 6 in many applications drive demand (Norberg, 2003).

2.3.1.7 Environmental impacts

Using data in the public domain, first estimates were made for the environmental impacts related to the production of PTT from bio-based PDO. Data were only available for the bio-based production of PDO via fermentation of glycerol (Grothe, 2000) which have been combined with information from various sources on the petrochemical production of (purified) terephthalic acid (PTA) and on the polymerisation stage (among them Boustead, 1999/2000). As Figure 2-10 shows the total energy requirements for the production of PTT are 16% lower than for PET, while the fossil CO_2 emissions are practically the same. The slight differences between PET and PTT related to the use of PTA (see Figure 2-10) are a consequence of different stoichiometric relationships for the two polymers. Energy use and emissions related to the polymerisation step are comparable in the two cases. Hence the difference in the totals mainly originates from the alcohol component: The energy use related to the diol component is clearly lower in the case of PTT compared to PET while, for carbon dioxide, its contribution is somewhat higher in the case of PTT. The similar values for CO_2 emissions are a consequence of comparable (fossil) *process* energy requirements for the production of PDO and ethylene glycol; in addition, stoichiometry plays a small role, leading to slightly higher emissions for the diol component in the case of PTT. The larger energy input for the diol component in the case of PET is caused by the fossil *feedstock* for ethylene glycol which is not required for PDO.

It should be noted that the results shown in Figure 2-10 refer to the production of PDO from glycerol (i.e. the route originally investigated by Shell, see Section 2.3.1), while DuPont's new fermentative process is based on glucose. The environmental impacts of DuPont's new process may hence be substantially lower (no results have been published to date). On the other hand, the results presented in Figure 2-10 are based on the assumption that the glycerol used is available as a byproduct without any environmental impacts (it was assumed that all impacts are allocated to the main product, i.e. rapeseed oil methyl ester). It is unclear whether these two assumptions – a possibly more disadvantageous raw material than to be used by DuPont on the one hand and an allocation method leading to lower environmental impacts on the other – compensate each other. It is intended to investigate these aspects in depth in the BREW project (BREW, 2003).

Figure 2-10: Cradle-to-factory gate energy use and CO_2 emissions for petrochemical PET and (partially) bio-based PTT (based on PDO from glycerol) (data for PET originate primarily from Boustead, 1999-2000; data for PTT are preliminary estimates based on various sources; see text)



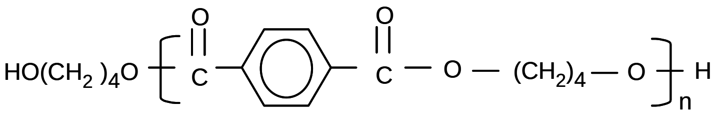
2.3.2 PBT from bio-based BDO

Much of the discussion concerning Poly(butylene terephthalate) (PBT) is analogous to that for PTT (section 2.3.1), apart from two major differences. Firstly, PBT can also be produced from a bio-based monomer and a number of studies have been carried out in recent years, but the results (to the best of our knowledge) have not yet led to an economically viable process. DuPont's recent success with bio-based 1,3-PDO could well provide stimulus to those interested in developing a commercial bioroute to BDO, but in the meantime the discussion of bio-based PBT is limited to the realm of the theoretical. Secondly, whereas PTT is only now emerging on the market, petrochemical-based PBT is already well established, with demand growing strongly: in 1997 the global demand for PBT was about 340,000 tonnes and the long-term average growth rate is about 6.2% (Morgan, 2001). This section will thus be limited to a description of a possible bio-based route to BDO as a monomer platform for PBT, substitution potential and pricing issues for bio-based versus petrochemical-based PBT, and a brief assessment of market prospects for PBT in general.

2.3.2.1 Production

Poly(butylene terephthalate) (PBT) (Figure 2-11) is a linear aromatic polyester produced by transesterification and polycondensation of dimethyl terephthalate (DMT) with 1,4-butanediol (BDO). PBT can also be produced from purified terephthalic acid (PTA) and BDO. The reaction scheme is similar to Figure 2-8, except with BDO in place of PDO.

Figure 2-11: PBT molecule



Conventional processes for the synthesis of BDO use petrochemical feedstocks, the most common being the Reppe process using acteylene and formaldehyde followed by hydrogenation of the intermediate to produce BDO (AZOM, 2003). An alternative bio-based process described by Smith, Cooper and Vigon (2001) involves three steps: corn-derived glucose is fermented to succinic acid, succinic acid is then purified by electrodialysis, then purified succinic acid is reduced catalytically to BDO.

PBT plants currently being built use continuous polymerisation (replacing old converted PET batch plants). The new continuous processes produce high intrinsic viscosity PBT without further processing steps (Thiele, 2001). The material quality from the new plants is also expected to be more consistent than that of the materials produced in the old converted PET plants.

2.3.2.2 Properties

PBT is a semi-crystalline, white or off-white polyester similar in both composition and properties PET and PTT (Table 2-14). The crystallinity of PBT imparts good strength, stiffness and creep resistance to finished products. Compared to PET, PBT has somewhat lower strength and stiffness, is a little softer but has higher impact strength and very similar chemical resistance. PBT's crystallisation temperature is in the range of 80-120 °C (as for PTT), and thus much higher than that of PET (130-150 °C) (Thiele, 2001). As it crystallises more rapidly than PET it tends to be preferred for industrial scale moulding; e.g. of electrical and automotive components (AZOM, 2003). PBT has a high continuous use temperature compared to other thermoplastics, has excellent electrical properties, and can be easily made flame retardant. It also has superior dimensional stability and good chemical resistance, particularly to organic solvents and oils (Morgan, 1998).

2.3.2.3 Technical substitution potential

As for PTT, the theoretical substitution potential of bio-based PBT for conventional PBT (assuming identical property sets) is 100%, while practical substitution depends essentially on price relativity.

PBT has a similar substitution profile to PTT (2-16), except with a higher degree of substitution for PC and slightly less substitution for PA and PET. PBT can substitute for phenolic resins and related materials in thermoset applications such as automotive electrical systems and connectors (Morgan, 1998). PBT has similar properties to PTT and a number of newly-developed aliphatic ketones in some markets, but substitution is more likely to proceed the other way around (i.e. replacement of PBT) due to the relatively high price of PBT.

2.3.2.4 Applications today and tomorrow

The discussion of applications and future markets relates to PBT in general rather than bio-based PBT. PBT is mostly used in compounded and alloyed form (e.g. with an amorphous polymer such as polycarbonate) in high performance applications. Major end-use sectors include the electrical and electronic (E&E) and transportation sectors (Morgan 1998). An example of a recent development in the E&E sector is PBT for fibre cable sheathing. Other applications in E&E include electrical insulation of household equipment, relay capstans, connecting cable, components for switches, and spark plug cases (Kamm and Schüller, 1997). New compounds and flame-retardant compositions for engineering plastic applications are also expected to be developed (Thiele, 2001). As PBT becomes available in larger amounts and at a lower price, the field of applications will widen and interest in textile spinning might even be revived.

2.3.2.5 Current and emerging producers

As already discussed, the status of bio-based BDO and producers interested in this possibility is not known. Conventional PBT however is currently in a growth acceleration phase with four new PBT projects planned to come on stream in 2003/4, at a total design capacity of 600 t/d (219 kt.p.a.). Most of these new plants will replace the remaining high-cost discontinuous production lines, which are mostly converted PET lines (Thiele, 2001). The total global demand for PBT in 2003 is estimated at 488,000 t.p.a.[12], so these new plants will supply about half of the global demand, assuming operation at full capacity.

2.3.2.6 Expected developments in cost structure and selling price

The cost structure of PBT manufacture is not known but could be expected to be somewhere in the vicinity of that for PTT. The current market price of petrochemical-based PBT resin (all US market prices) is in the range of € 2.00 - € 2.30 per kg for PBT injection (Plasticsnews, 2003) and € 2.85 - € 3.00 per kg for PBT unfilled resin (PTO, 2003). This clearly places PBT in the engineering thermoplastics, as opposed to PET which is classified in the volume thermoplastics at roughly half this price: PET bottle grade is priced at € 1.45 - € 1.55 (PTO, 2003). The market price for PBT from bio-based BDO is not expected to change from the current market price.

2.3.2.7 Environmental impacts

No verified results on environmental impacts are available for Poly(butylene terephthalate) (PBT). A preliminary energy analysis has been conducted for this study using a publication by Cooper and Vigon (2001) on the environmental profile of bio-based versus petrochemical 1,4-butanediol (BDO). As a (preliminary) result, the (cradle-to-factory gate) energy use for bio-based PBT has been determined to be about 10% lower than that of petrochemical PBT. Since the study by Cooper and Vigon (2001) does not provide any information on the type of the bio-based process, its development stage and the scale of production it is not justifiable to use these results without further verification.

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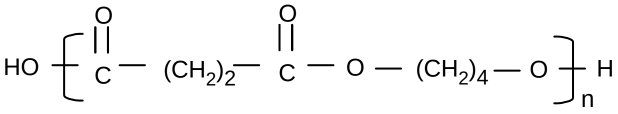
[12] From Section 2.3.2: in 1997 the global demand for PBT was about 340,000 tonnes and the long-term average growth rate is about 6.2% (Morgan, 2001). From this an estimate for 2003 demand has been calculated.

2.3.3 PBS from bio-based succinic acid

Poly(butylene succinate) (PBS) (Figure 2-12) is a biodegradable synthetic aliphatic polyester with similar properties to PET. It has excellent mechanical properties and can be applied to a range of end applications via conventional melt processing techniques. Applications include mulch film, packaging film, bags and flushable hygiene products (Nandini, 2003). PBS is generally blended with other compounds, such as thermoplastic starch and adipate copolymers (to form PBSA) to make its use more economical.

Figure 2-12: PBS molecule



$$HO-\left[\overset{O}{\overset{\|}{C}}-(CH_2)_2-\overset{O}{\overset{\|}{C}}-O-(CH_2)_4-O\right]_n-H$$

One of the monomers for PBS is succinic acid, a dicarboxylic acid previously of little commercial interest which has been the subject of much R&D of late, particularly in Japan, due to the increasing attention on new polyesters with good mechanical properties combined with full biodegradability and the potential for manufacture from renewable feedstocks (Lockwood, 1979). While Showa HighPolymer (the only known bulk producer of PBS) employs a process based on petrochemical monomers, Mitsubishi Chemical and Ajinimoto are reported to be developing a bioroute to succinic acid. Mitsubishi will produce PBS from bio-based succinic acid and claims that this will be much cheaper than polylactic acid (PLA) and could replace it in several applications (Nandini, 2003).

2.3.3.1 Production

PBS is currently produced by condensation polymerisation of petrochemical-based succinic acid and 1,4-butanediol (BDO), both of which are usually derived from maleic anhydride (Nandini, 2003).

In the bioroute succinic acid may be produced together with oxalic acid, fumaric acid and malic acid in submerged culture anaerobic fermentation by various types of bacteria and molds (Lockwood, 1979). Succinic acid can also be converted via maleic anhydride to butanediol (Nandini, 2003). Succinate concentration as high as 110 g/l have been achieved from glucose by the rumen organism *Actinobacillus succinogenes* (Liu, 2000). It can also be produced by *Anarobiospirillum succiniciproducens* using glucose or even lactose, sucrose, maltose, and fructose as carbon sources.

2.3.3.2 Properties

PBS (Table 2-14) is a white crystalline thermoplastic with density (as for PLA) of 1.25, melting point much higher than PLA and lower than P(3HB-co-3V) and a very low glass transition temperature. It has generally excellent mechanical properties and processability. Like other aliphatic polyesters, it is thermal stable up to approximately 200 °C (for aromatic polyesters this is much lower). It has good dyeing characteristics and is biodegradable.

PBS may be processed using conventional polyolefin equipment in the temperature range 160-200 ºC to manufacture injection, extrusion or blown moulded products. New grades of PBS copolymers have recently been produced with a high recrystallisation rate and high melt tension, suitable for preparing stretched blown films and highly expanded foams.

2.3.3.3 Technical substitution potential

PBS can substitute for PET; also for PP. Mitsubishi claims that PBS can replace polyolefins (PE, PP) and polystyrene in some applications; additionally it can replace PLA in several applications (Nandini, 2003). Showa HP (2003) also suggests substitution potential is highest for PE-LD, PE-HD and PP; as well as non-polymeric materials including paper, natural fibre and wood.

2.3.3.4 Applications today and tomorrow

PBS finds applications in mulch film, packaging, bags, flushable hygiene products and as a non-migrating plasticiser for PVC. Showa HighPolymer, who provided a breakdown of the market for the company's PBS products (Table 2-17) cites strong growth in agricultural mulch film and foamed cushioning and specifies food packaging and engineering works material as other future growth areas. Mitsubishi is targeting the market being developed by Cargill Dow for PLA; i.e. packaging, fibres and mulch film (Nandini, 2003).

Showa also produces a grade of Bionolle® which has a long chain branch, high melt tension and high recrystallisation rate, suitable for the manufacture of stretched blown bottles and highly expanded foams (Liu, 2000).

Table 2-17: Main applications for PBS and PBSA – share of interviewed company's[1] total production by market sector (scope: global)[2]

Sector	% of total production today	% of total production in 2020
Packaging[3]	25	57.5
Building	5	7.5
Agriculture	50	15
Transportation	10	10
Furniture	4	5
Electrical appliances and electronics (E&E)	2	5
Houseware	4	5
Others		-
Total	100	100

[1] Showa HP (2003);

[2] Breakdown of current market (t.p.a.): EU-15: 20; Japan: 1445; other: 35;

[3] Includes compost bag (10% today, 7.5% in 2020).

2.3.3.5 Current and emerging producers

Mitsubishi Chemical and Ajinimoto are reported to be developing a bioroute to succinic acid. Mitsubishi will produce PBS from bio-based succinic acid and claim that this will be much cheaper than polylactic acid (PLA) and could replace it in several applications (Nandini, 2003).

The main producer of PBS is Showa Highpolymer, part of the Showa Denko Group, in Japan. Showa produces PBS and PBSA[13] at a combined capacity of 3,000 t.p.a. and plans to double this capacity to 6,000 t.p.a. Production in 2002 was 1500 t and cumulative production since plant start-up is 6000 t (Nandini, 2003).(Showa HP, 2003). SK Polymers, Korea is also reported to have a small plant producing PBS and PBS-A (trade name SkyGreen BDP).

The first bio-based PBS is likely to be produced by Mitsubishi Chemical. Mitsubishi has plans to produce 3,000 t.p.a. of PBS for use as garbage bags and agricultural films. The process for bio-based succinic acid is being developed by Mitsubishi together with Ajinimoto. The plan is to have a succinic acid plant with an initial capacity of 30,000 t.p.a. by 2006, to be located outside Japan in a region with a suitable supply of crops. Mitsubishi says its bio-based PBS is likely to be much cheaper than poly(lactic acid) in several applications (Nandini, 2003).

2.3.3.6 Expected developments in cost structure and selling price

Showa HighPolymer sells Bionolle® PBS for € 3.50 per kilo and expects this price to go down only marginally to € 3.00 per kilo (Showa HP, 2003)[14]. It is expected that PBS with a bio-based component will be competitively priced with Showa's product, since Mitsubishi's target is to match the price of PLA.
According to Showa HP (2003) (referring to the petrochemical production route), the raw material has the most influence on the cost price; followed by the scale of production. Showa claims that the percentage of costs attributed to the feedstock will increase (from 50% in 2003 to 85% in 2030).

Showa's projections are in sharp contrast to the expected **decrease** in raw material cost (both in absolute terms and relative to total costs) which is expected for the bio-based route. Specifically, new developments in end product recovery are reported to have lowered the cost of succinic acid production to U.S. $ 0.55 (€ 0.50) per kg at the 75,000 tonne per year scale and to U.S. $ 2.20 (€ 1.96) per kg at the 5,000 t.p.a. scale (Liu, 2000).

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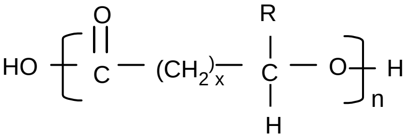
[13] PBS: Bionolle #1000, Bionolle #1903; PBSA: Bionolle #3000, other products: Bionolle 5151.

[14] (P&G, 2002) gives a higher figure of € 5.00 per kilo.

2.4 Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs), consiting a class of bio-based polyesters with highly attractive qualities for thermoprocessing applications, have not yet entered bulk markets due to high production costs. Like PLA, PHAs are aliphatic polyesters produced via fermentation of renewable feedstocks. Whereas PLA production is a two-stage process (fermentation to monomer followed by a conventional polymerisation step), PHAs are produced directly via fermentation of carbon substrate within the microorganism. The PHA accumulates as granules within the cytoplasm of cells and serves as a microbial energy reserve material (OTA, 1993). PHAs have a semicrystalline structure, the degree of crystallinity ranging from about 40% to around 80% (Abe and Doi, 1999).

Figure 2-13: PHA molecule



$$\mathrm{HO}\left[\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_x-\underset{\underset{\displaystyle H}{|}}{\overset{\overset{\displaystyle R}{|}}{C}}-O\right]_n\mathrm{H}$$

Figure 2-13 shows the generic formula for PHAs where x is 1 (for all commercially – relevant polymers) and R can be hydrogen or hydrocarbon chains of up to around C16 in length. A wide range of PHA homopolymers, copolymers, and terpolymers have been produced, in most cases at the laboratory scale. The main members of the PHA family are the homopolymers poly(3-hydroxybutyrate), P(3HB), which is the above generic formula with R=1(methyl), and poly(3-hydroxyvalerate), P(3HV), generic formula with R=2(ethyl). PHAs containing 3-hydroxy acids have a chiral centre and hence are optically active (Metabolix, 2003)

Copolymers of PHAs vary in the type and proportion of monomers, and are typically random in sequence. Poly(3-hydroxybutyrate – co-3-hydroxyvalerate), P(3HB-*co*-3HV), trade name Biopol®, is made up of a random arrangement of the monomers R=1 and R=2. Poly(3-hydroxybutyrate – co-3-hydroxyhexanoate), P(3HB-*co*-3HHx), consists of the monomers R=1(ethyl) and R=3(propyl). The Nodax® family of copolymers, are poly(3-hydroxybutyrate-*co*-3-hydroxyalkanoate)s with co-polymer content varying from 3–15 mol % and chain length from C7 up to C19 (P&G, 2001).

The range of PHA structural architectures that is now accessible has opened up a broad property space, encompassing rigid thermoplastics, thermoplastic elastomers, as well as grades useful in waxes, adhesives, and binders (Metabolix, 2003). Table 2-18 lists the major PHAs that have been the subject of ongoing investigations and commercialisation efforts in recent years. Not included in this table but also under investigation are 4HB-containing PHAs. According to Steinbüchel and Lütke-Eversloh (2003), there are reasonable prospects for 4HB-containing PHAs, which have promising mechanical properties, to be obtained from cheap carbon sources such as glucose and 1,4-butanediol by employing engineered organisms.

Table 2-18: The structure of basic PHAs and those of commercial interest[1]

PHA	3-hydroxy acids with side chain R
P(3HB)	$-CH_3$
P(3HV)	$-CH_2CH_3$
P(3HB-*co*-3HV) (Biopol®)[2]	$-CH_3$ and $–CH_2CH_2CH_3$
P(3HB-*co*-3HHx) (Kaneka)[3], (Nodax®)[4]	$-CH_3$ and $–(CH_2)_2CH_3$
P(3HB-*co*-3HO) (Nodax®)	$-CH_3$ and $–(CH_2)_4CH_3$
P(3HB-*co*-3HOd) (Nodax®)	$-CH_3$ and $–(CH_2)_{14}CH_3$

[1] (P&G, 2002);
[2] Patent held by Metabolix, Inc.;
[3] Kaneka holds the patent on chemical composition;
[4] P&G holds processing and application patents.

Commercialisation of P(3HB), the prototype of the PHA family, was first attempted by W. R. Grace Co. in the 1950s (OTA 1993). In the mid-70's, Zeneca (formerly ICI) Bio Products produced several tons of a series of PHA copolymers under the trade name Biopol®. In the period 1982-88, Chemie Linz GmbH in collaboration with Petrochemia Danubia (PCD) produced P(3HB) from sucrose as substrate and in 1991 commenced pilot production of 2 tonnes (Biomer, 2003). In the early 1990s Zeneca UK produced P(3HB-*co*-3HV) by bacterial fermentation using a mixture of glucose and propionic acid. At the time, Zeneca's pilot plant polymer was offered at US $30 per kg and material from a 5000 tons/year semi-commercial plant was projected to go down to US $8-10 per kg, still a prohibitive price for bulk applications.

In 1996, Zeneca sold its Biopol business to Monsanto, who continued investigations started by Zeneca into production of PHA in genetically-modified crops; specifically, the expression of PHA-synthesizing genes in rapeseed. In parallel, Monsanto commercially produced small volumes of Biopol® P(3HB-*co*-3HV) by means of fermentation. In 1998, Monsanto ceased its PHA operations (Bohlmann, 2000) and in 2001 sold its Biopol® assets to the U.S. biotechnology company Metabolix (Metabolix, 2003). Today, Metabolix is producing PHAs through fermentation of commercial-grade corn sugar in a 50 cubic metre fermenter. Metabolix has achieved high production rates and titres with overall fermentation times of less than 40 hours, and claims that targets for commercially-viable production of PHA are within reach. In parallel, Metabolix continues R&D on PHA production in genetically modified crops.

A company not generally associated with the field of biotechnology, Procter & Gamble (P&G) has engaged in R&D efforts to develop and commercialise the Nodax® range of PHAs (P&G, 2003). P&G has patented recovery and processing routes for these polymers which it has licensed to the Japanese company Kaneka Corporation. Kaneka is developing the commercial process and is expected to be producing bulk volumes (20,000 t.p.a. or more) of P(3HB-*co*-3HHx) by early 2005. For commercial viability PHA concentrations of 60 to preferably 80 g/l should be reached (P&G, 2001).

Feedstocks currently being utilised for PHA production are high value substrates such as sucrose, vegetable oils and fatty acids. In theory, any carbon source can be utilised, including lignocellulosics from agricultural by-products. In practice, as for PLA and the other polyesters already discussed, further improvements in fermentation yields by metabolic engineering of microorganisms, together with technological advances in feedstock pretreatment (e.g. new enzymatic processes) are prerequisites for a shift to lower-value feedstocks.

2.4.1 Production of PHAs

Production by Fermentation

A generic process for PHA produced by bacterial fermentation consists of three basic steps: fermentation, isolation and purification and blending and palletising (P&G, 2003). Subsequent to inoculation and small-scale fermentation, a large fermentation vessel is filled with mineral medium and inoculated with seed ferment (containing the microbe or bacteria). The carbon source is fed at various rates until it is completely consumed and cell growth and PHA accumulation is complete. The bacteria can be fed a range of different carbon sources; e.g. *E.coli* fed with a range of oils (lipids, saccharides etc.) as a food source produces different compositions of Nodax®; *R. eutropha* fed with a combination of glucose and propionate produces Biopol® P(3HB-*co*-3HV) (Asrar and Gruys, 2001). The total fermentation step typically takes 38 to 48 hours. To isolate and purify PHA, the cells are concentrated, dried and extracted with hot solvent. The residual cell debris is removed from the solvent containing dissolved PHA by solid-liquid separation process. The PHA is then precipitated by addition of a non-solvent and recovered by solid-liquid separation process. PHA is washed with solvent to enhance the quality and dried under vacuum and moderate temperatures (in certain cases where high purity product is not needed, solvent extraction may not be required). The neat polymer is packaged for shipping. Separately the solvents are distilled and recycled. The neat polymer is typically pre-formed in pellets with or without other polymer ingredients based on down stream application needs.

Production in crops

The technology is being developed to produce PHAs in specific plant tissues, such as seeds or leaves, directly by photosynthesis using carbon dioxide and water as the raw materials. Many attempts have been made to produce PHAs directly in plants, but so far all have fallen short of demonstrating an economic system. Metabolix claims to be making significant progress with metabolic engineering to produce PHAs in high yields directly in non-food, industrial crop plants (Metabolix 2003).

Current and future feedstocks

Currently, the type of feedstock varies greatly depending on the grade of product desired and the microorganism used in the fermentation. Important carbon sources for producing PHA today (classic substrates in defined media) include (Braunegg, 2002):

- **Carbohydrates:** glucose, fructose, sucrose.
- **Alcohols:** methanol, glycerol
- **Alkanes:** hexane to dodecane
- **Organic acids:** butyrate upwards

In the US, the raw material source today is chiefly corn steep liquor; in the EU beet sugar predominates. High value feedstocks such as palm kernel or soybean oil are also used with some microorganisms.

If PHA by fermentation is to attain bulk commercial viability as well as to further improve its sustainability profile, production must be from cheap renewable resources, with complex growth and production media. Possibilities include:

- **Carbohydrates**: Molasses, starch and whey hydrolysates (maltose), lactose from whey, cellulose hydrolysates (e.g. paper industry waste)
- **Alcohols:** Wastes from biodiesel production: methanol plus glycerol, methanol
- **Fats and oils:** lipids from plant and animal wastes
- **Organic acids**: lactic acid from the dairy industry

Theoretical yield calculations have already been performed for many possible feedstocks. The result of one such calculation (The Wheypol Process) shows that the 50 x 10^6 metric tonnes of whey produced annually in Europe could be used to produce 618,000 metric tonnes of P(HB-*co*-15%HV) (Braunegg, 2002).

2.4.2 Properties

The chemical, mechanical and thermal properties of PHAs are given in Table 2-19. In the discussion of material properties, a distinction will be drawn between P(3HB) homopolymer (as produced by Biomer), P(3HB-*co*-3HV) di-copolymer as produced by Metabolix and P(3HB-*co*-3HHx) medium-branch chain di-copolymer as produced by Kaneka / Procter and Gamble.

Physical Properties

PHAs are available in molecular weights ranging from around 1,000 to over one million (Metabolix, 2003). Varying the chain length in the PHA subunit (monomer) affects hydrophobicity and a number of other properties including the glass transition temperature, the melting point, and level of crystallinity (Metabolix, 2003). PHA film is translucent and injection molded articles from PHAs have high gloss.

Mechanical and Thermal Properties

P(3HB) has good thermoplastic properties (melting point 180°C) and can be processed as classic thermoplasts and melt spun into fibres. It has a wide in-use temperature range (articles retain their original shape) from -30°C to 120°C. Perishable goods can be canned into packages produced of P(3HB) and preserved by steam sterilization. Articles made of P(3HB) can be autoclaved (Biomer, 2003). However, it is fairly stiff and brittle, somewhat limiting applications. PHB has a small tendency to creep and exhibits shrinkage of 1.3 %.

The copolymer P(3HB-*co*-3HV) has lower crystallinity and improved mechanical properties (decreased stiffness and brittleness, increased tensile strength and toughness) compared to P(3HB), while still being readily biodegradable. It also has a higher melt viscosity, which is a desirable property for extrusion blowing.

Medium chain length PHAs are elastomers and have a much lower melting point and glass transition temperature (Weber, 2000). Their molecular structure is analagous to soft polypropylene. This is due to chain defects which cause crystal disruption and enhanced molecular entanglement, resulting in a highly amorphous material.

Table 2-19: Properties of PHAs

	P(3HB) (Biomer® P240)[1]	P(3HB) (Biomer® P226)[1]	P(3HB-*co*-3HV) (Biopol®)[2]	P(3HB-*co*-3HHx) (Kaneka, Nodax®)[3]
Physical properties				
Melt flow rate (g/10 min)	5-7	9-13		0.1-100
Density (g/cm^3)	1.17	1.25	1.23-1.26	1.07-1.25
Transparency (%)			0.7	white powder / translucent film
Mechanical properties				
Tensile strength at yield (MPa)	18-20	24-27		10-20
Elongation at yield (%)	10-17	6-9		10-25
Flexular Modulus (MPa)	1000-1200	1700-2000	40	several orders of magnitude
Thermal properties				
HDT (°C)	-	-		60-100
VICAT Softening point (°C)	53	96		60-120

[1] (Biomer, 2003)
[2] (Metabolix, 2003); (Asrar, 2001);
[3] (P&G, 2003)

For copolymers with C4 and higher branching, the mechanical properties are similar to those of high grade polyethylene. The Young's Modulus (stiffness) and the yield stress lie between HDPE and LDPE; both are reduced with increasing the content and size of the branches (P&G, 2002). The length of comonomer branches improves both the toughness and ultimate elongation. The crystallisation rate of these PHAs (specifically, Nodax®) is reported to be too slow for film blowing (P&G, 2002), restricting its usefulness in this application prior to blending with other more easily crystallising polymers.

Other Properties

P(3HB) is water insoluble and relatively resistant to hydrolytic degradation. This differentiates P(3HB) from most other currently available bio-based plastics which are either moisture sensitive or water soluble (Jogdand, 2003). Due to P(3HB)'s high crystallinity (60 to 70%) it has excellent resistance to solvents. Resistance to fats and oils is fair to good. It has good UV resistance, but poor resistance to acids and bases. The oxygen permeability is very low (2 x lower than PET, 40 x lower than PE), making P(3HB) a suitable material for use in packaging oxygen-sensitive products. P(3HB) has low water vapour permeability compared to other bio-based polymers but higher than most standard polyolefins and synthetic polyesters.

Medium-length copolymers, e.g. P(3HB-*co*-3HO), can be dyed with an aqueous dispersion of non-ionic dyes at room temperature, in a similar process to the commercial polyester fibre dyeing process (P&G, 2002). They are melt compatible with typical polyester dyes and pigments. P(3HB) is difficult to dye since it is highly crystalline.

P(3HB) is free from even traces of catalysts and is toxicologically safe (Biomer, 2003). The monomer and the polymer are natural components and metabolites of human cells. Thus P(3HB) formulations can be used for articles which come into contact with skin, feed or food (Biomer is in the process of registering its PHA products for food contact).

PHAs are fully biodegradable in both anaerobic and aerobic conditions; also at a slower rate in marine environments (P&G, 2002). Without composting conditions they remain intact for years (Biomer, 2003). PHAs are also chemically digestible in hot alkaline solutions.

Conversion Technologies

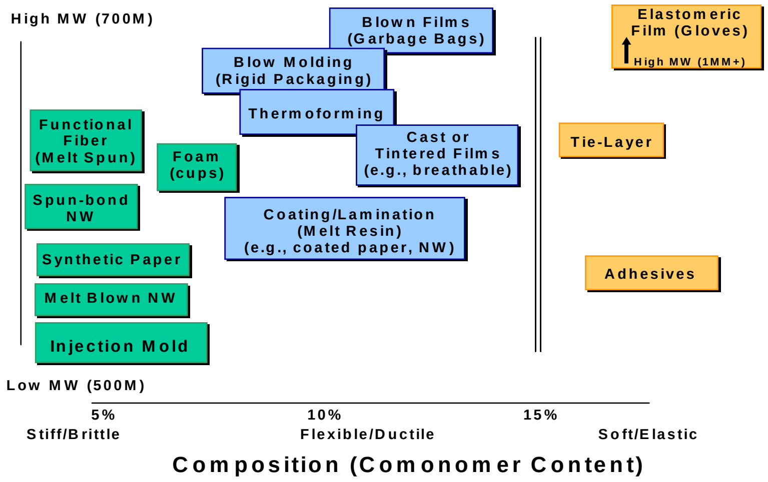
Depending on the range of material properties discussed above, but primarily on the chemical composition and the molecular weight, PHAs can be converted to a range of finished products including films and sheets; molded articles; fibres; elastics; laminates and coated articles; nonwoven fabrics; synthetic paper products and foams (P&G, 2002).

The suitability of PHAs to the various thermoplastic conversion technologies is best summarised in Figure 2-14. At low comonomer content and low molecular weight, PHAs are suitable for injection moulding and melt blowing. At medium molecular weight, the material is suitable for melt spun fibres. With higher comonomer content and medium molecular weight (600,000), applications include melt resins and cast films. Blown films and blow moulding require at least 10% comonomer content and high molecular weight (700,000). Above 15% comonomer, the PHAs are softer and more elastic, finding application in adhesives and elastomeric film.

Fillers and blends

To improve stiffness and strength, also to enhance barrier properties and increase the opacity, PHA base (co)polymer may be blended with inorganics such as $CaCO_3$, talc and mica (P&G, 2002). Functional fillers include pigments and carbon black for colouring, fibers for structural reinforcement and rubber for impact strength. Bio-based polymers including thermoplastic starch, chitin and PLA may be added to control the rate of degradation and/or disintegration. Co-polymers for PHAs could also be of synthetic origin should this be what the market wants (P&G, 2003).

Figure 2-14: Processing technologies for medium chain length PHA copolymers by composition and molecular weight. (P&G 2002), reprinted with permission).



According to Procter & Gamble, alloys (blends) of Nodax® PHA and PLA are particularly promising. Property deficiencies of either single polymer can be eliminated by blending. Referring to the comparison in Table 2-20, one can see that PLA is available in larger quantities and at a lower price than PHA; PLA is also more transparent and tougher than PHA. PLA improves PHA's tensile strength and processability. The two materials have similar wettability, providing even, consistent blend characteristics for wicking, dyeing and printing. PHA improves PLA degradation, high temperature hydrolytic stability and barrier properties and provides heat sealability.

Table 2-20: Comparison of properties for PLA and branched PHA copolymers (P&G, 2002)

PLA	PHA (Nodax®)
Physical properties	
often amorphous	semicrystalline
transparent	usually opaque
brittle, hard, stiff	tough, ductile
use temperature <60 °C	use temperature <120 °C
Degradation Mechanisms	
hydrolitic attack	enzymatic digestion
not directly biodegradable	rapid biotic degradation
temperature, pH, and moisture effect	aerobic or anaerobic conditions
spontaneous degradation	relatively stable in ambient conditions
Processability	
quick quench	slow crystallisation
fibre spinning	films, fibres

Blends of PHA with thermoplastic starch (TPS) are also under development. Starch is cheaper and more plentiful than PHA. The starch content allows tailoring of disintegration and degradation characteristics. PHA's lower melt temperature prevents starch degradation during processing. PHA also improves the hydrolytic and UV stability of starch, reduces noise, increases clarity and improves barrier properties. Nodax® and starch have been co-spun (without phase mixing of the starch and polymer melt) to make meltspun fibres, nonwoven webs and disposable articles with rapid biodegradation characteristics (e.g. diapers). (Nodax3).

2.4.3 Technical substitution potential

Table 2-21 shows the substitution potential for PHAs, as perceived by representatives of Procter & Gamble and Biomer. In terms of technical substitution it may be concluded that *PHB homopolymer* has good potential to substitute for PP and some potential to substitute for **PE-HD**, **PS** and **ABS**; while the greatest potential for *medium chain length branched PHA copolymers* lies with substituting for **PE-HD**, **PE-LD** and **PP**. To a lesser extent, substitution for **PVC**, **PET** and **PUR** could take place. Non-polymers, specifically wood and paper, could also be substituted in niche applications; for example, Procter & Gamble have prototyped paper out of 100% Nodax® pulp and 90% Nodax®/10% Kraft pulp (P&G, 2002).

Table 2-21: Technical substitution potential for PHAs according to interviews with experts from P&G and Biomer.
++ *full substitution* + *partial substitution* - *no substitution*

	PVC	PE-HD	PE-LD	PP	PS	PMMA	PA	PET	PBT	PC	POM	PUR	ABS	non-poly
P&G[1] Nodax®	+	++	++	++	-	-	-	+	-	-	-	+	-	+[3]
Biomer[2] P(3HB)	-	+	-	++	+	-	-	-	-	-	-	-	+	

[1] (P&G, 2003) (Nodax®);
[2] (Biomer, 2003b);
[3] Wood, paper.

2.4.4 Applications today and tomorrow

As for PLA, producers are not only looking at PHA's potential for substitution in conventional applications. PHA also shows promise in many novel applications where non-toxicity, biodegradability and increasingly, the use of renewable feedstocks are prerequisites that conventional synthetic thermoplastic polymers cannot meet.

Procter & Gamble (P&G, 2003) has identified a wide range of applications for Nodax® PHAs, presented in Appendix 1. According to Appendix 1, the market potential varies between 3% for certain identified applications up to 100% for others, with a total estimated market potential for compounded Nodax® resin of 1,174,000 short tons per year. In assessing and developing the commercial basis for Nodax®, P&G considers not only direct substitution possibilities but also novel properties in both the in-use phase and the end-of-life phase. A few interesting examples may be given:

- Flushable hygiene products (e.g. tampons) made of PHA provide end-of-life benefits to the consumer in the form of convenience, discretion and hygiene. In addition, steps associated with the used product being transported to then disposed of in a waste management facility are eliminated.
- Adding a layer of Nodax® PHA to a bulk structure made of another bio-based polymer, as in clam-shells for fast food packaging made of a starch blend. The PHA layer provides a heat and moisture barrier, as well as a reasonable odour and a printable surface. PHA has good affinity for starch so the layer adheres well. It also has a similar degradation profile to starch blend polymers.
- Use of Nodax® in the Alcantara process for the production of artificial suede (invented by Toray). Nodax® and starch are dissolved during process. Whereas the standard Alcantara process uses trichloroethylene, the Nodax®/starch process eliminates VOC issues related to solvent handling.
- In existing systems, Nodax® (or another biopolymer) can play a role in reducing the load on plastics recycling systems. The labels and closures for detergent bottles are currently made of PP, causing problems for recycling of the HDPE bottle. If these are replaced by Nodax®, then during the standard cleaning process involving chemical digestion in slightly alkaline medium the Nodax® is completely digested. The extra energy requirements (embodied + processing energy for Nodax® versus HDPE) for a much simpler process are almost negligible. This is perhaps a different (or complementary) strategy to straight replacement based on physical properties, relative costs and ecological credentials.
- One promising area for ‘straight’ substitution is biodegradable mulch film made from a combination of Nodax® and starch to replace banned starch/PE blends.

Biomer (Biomer, 2003b) being a specialty producer has quite a different market focus at present and currently limited to supplying PHA for niche applications and analytics. Biomer expects that by 2030 70% of PHAs will be used in packaging.

2.4.5 Current and emerging producers

The main companies with plans for large volume production of PHAs are the US companies Metabolix Inc. with Biopol® P(3HB-*co*-3HV) and Procter and Gamble (P&G), in partnership with Kaneka Corporation, Japan with P(3HB-*co*-3HHx) Nodax®.

As outlined in Section 2.4, **Metabolix** is producing Biopol® in a 50 m^3 fermenter, with overall fermentation times of less than 40 hours. Assuming a final concentration of 100 $g.L^{-1}$ which is a reasonable estimate for newer bacterial strains (Rediff, 2003), this gives an estimated annual capacity of 1,100 t.p.a. In addition to its efforts to commercialise Biopol®, Metabolix is coordinating a US $1.6 million project funded by the US Department of Commerce’s Advanced Technology Program, the goal of which is to re-engineer the central metabolism of E. coli for more efficient conversion of renewable sugars into PHAs (Metabolix, 2003). In August 2003, BASF signed a one-year collaboration agreement with Metabolix to further develop PHAs (TCE, 2003), indicating that interest from the bulk chemicals sector is growing.

Metabolix's parallel investigations into production of PHAs in crops have focused on a target PHA yield of 10% w/w in transgenic rapeseed (Wilke 1998). In 2001, Metabolix commenced coordination of a US $15 million cost-shared project funded by the U.S. Department of Energy. The five-year project will investigate the production of PHAs in green tissue plants such as switchgrass, tobacco, and alfalfa (Metabolix, 2003). Commercialisation of PHA produced in this way is estimated to be 5 to 10 years off, with a number of issues to be addressed include the need to preserve the genetic identity of the crop, public opinion related to genetically engineered crops and technical hurdles related to feedstock storage, yield improvement, and extraction and purification of PHA from the plant (Bohlmann, 2004).

Procter and Gamble (P&G) has extensive commercialisation plans for the Nodax® range of PHAs, to be produced in a partnership agreement by Kaneka Corp., Japan. P&G collaborates in its PHA developments with Tsingua University in China and the Riken Institute in Japan (P&G, 2003). P&G is investigating a wide range of applications for PHA co-polymers including films, fibres, nonwovens, aqueous dispersions and hygiene products. The company's standpoint is that it will be able to successfully compete in the synthetic polyester-dominated thermoplastics market, despite an inevitably higher price, when the novel functional qualities of PHAs are taken into account.

The biotechnology company **Biomer**, located in Krailling, Germany produces PHAs on a small-scale commercial basis for specialty applications (Biomer, 2003). In 1993 Biomer acquired the bacteria and know-how for the fermentative production of P(3HB) from the Austrian company PCD and in 1994-5 registered the trade name Biomer® for its PHA products. Biomer does not appear to have plans to move towards large-scale production.

Another company planning to enter the bulk PHA market is **PHB Industrial**, São Paulo, Brazil. This is 50/50 joint venture between sugar and alcohol producer Irmãos Biagi and the Balbo Group. The project is currently at pilot plant stage, producing 50 t.p.a. P(3HB) and P(3HB-*co*-3HV) from sugar cane. The company plans to construct a 10,000 t.p.a. (PHA blends and composites) plant for startup in 2006 (PHB IND, 2003).

In Japan, **Mitsubishi Gas Chemicals** (MCG) has made an in-depth development study of the production of P(3HB) from methanol fermentation (trade name Biogreen®). The company envisages extensive applications for Biogreen® as a reformer for other biodegradable resins (MGC, 1999).

2.4.6 Expected developments in cost structure and selling price

Selling price

To our knowledge, commercial sales of PHAs are limited to Biomer® P(3HB), for a price of € 20 per kg (Biomer, 2003b) and Metabolix's Biopol® for about € 10-12 per kg (Petersen et al., 1999). The price of PHAs in general is presently much higher than starch polymers and other bio-based polyesters due to high raw material costs, high processing costs (particularly purification of the fermentation broth), and small production volumes.

Cost of production

At present, the raw material costs account for a much as 40% to 50% of the total production cost for PHA. Use of lower cost carbon sources, recombinant *E.coli* or genetically engineered plants should all lead to reductions in the cost of production (Jognand, 2003).

Table 2-22 gives a target cost breakdown for the production of Nodax® when the commercial plant comes on line in 2005 (P&G, 2003). The target breakdown is also given for 2030. P&G believes that the cost of production for Nodax® must be reduced to US $1.50 per kg if bulk volume commercial viability is to be attained.

Expected price developments

Today the price for PHAs using a natural bacterial strain such as *A.eutrophus* is around US $16.00 per kg. With recombinant *E.coli*, the price could be reduced to US $4 per kg, which is much closer to other bio-based plastics such as PLA (Jognand, 2003).
Akiyama et al. (2003) have estimated the production cost for the fermentative production of two types of PHAs using a detailed process simulation model. According to their calculations the annual production of 5000 t p.a. of poly(3-hydroxybutyrate-*co*-5mol% 3-hydroxyhexanoate) [P(3HB-*co*-5mol% 3HHx), also referred to as P(3HA)] from soybean oil as the sole carbon source is estimated to cost from US $3.50 to $4.50 per kg, depending on the presumed process performance. Microbial production of poly(3-hydroxybutyrate) [P(3HB)] from glucose at a similar scale of production has been estimated to cost US $3.80-4.20 per kg.

Metabolix claims that its recent scale-up, together with patented recovery technology, demonstrates the basis for production of PHAs at costs well below US $2.40 per kg at full commercial scale (Metabolix, 2003).

P&G is targeting a market entry price in 2005 of US $2.50 to 3.00 per kg, based on a minimum capacity of 30,000 t.p.a. and more realistically, 50,000 t.p.a. Above this pricing the company believes that it will be difficult to provide an acceptable value equation for most consumer products.

Biomer expects a price for its P(3HB) between €3.00 to 5.00 per kg in 2030, to be driven by market requirements. This price is significantly higher than targets for Metabolix and P&G, reflecting Biomer's (current and planned) relatively smaller scale of production.

Table 2-22: Target cost breakdown for PHA production according to P&G[1], 2005 and 2030

Cost breakdown (in %)	**2005**	**2030**
Raw material cost	20-25%	10-15%
Capital cost	30-35%	15-20%
Labour cost	10-15%	10-15%
Operating cost	15-20%	30-35%
Other	15-20%	20-25%
Total	100%	100%

[1] P&G (2003)

2.4.7 Environmental impacts

The environmental impacts of polyhydroxyalkanoates (PHA) have been discussed controversially in the last few years and will therefore be dealt with here in somewhat more detail than for the other polymers. Again, the available studies focus on the energy requirements and CO_2 or greenhouse gas emissions only. Contrary to the environmental analyses for starch polymers and PLA, the results for PHA are based on simulations since no large-scale facility is available to date.

In Table 2-23 data for PHA by Gerngross and Slater (2000) are compared to LCA data for petrochemical polymers according to Boustead (1999-2000). The table shows that the total cradle-to-factory gate fossil energy requirements of PHA can compete with polyethylene (HDPE) depending on the type of the PHA production process. Compared to polyethylene terephthalate (PET), the minimum total energy input for PHA production (fermentation) is somewhat higher while it is lower compared to polystyrene (PS). In contrast, the process energy requirements of PHA are two to three times higher than for petrochemical polymers (Table 2-23). Limiting the discussion to these process energy data Gerngross and Slater drew the conclusion that polyhydroxyalkanoates do not offer any opportunities for emission reduction (Gerngross and Slater, 2000; Gerngross, 1999). This finding is valid for certain system boundaries, e.g. for the system "cradle-to-factory gate" the output of which are plastics pellets. The conclusion is also correct if all plastic waste is deposited in landfills. In contrast, the finding is not correct if other types of waste management processes are assumed within the "cradle-to-grave" concept. As the last column of Table 2-23 shows the total fossil energy requirements are practically identical for PE and PHA manufactured by bacterial fermentation. Hence, if combusted in a waste incinerator (without energy recovery), both plastics result in comparable CO_2 emissions throughout the life cycle.

Table 2-23: Energy requirements for plastics production (Gerngross and Slater, 2000; Boustead, 1999)

	Cradle-to-factory gate fossil energy requirements, in GJ/tonne plastic		
	Process energy	Feedstock energy	Total
PHA grown in corn plants	90	0	90
PHA by bacterial fermentation	81	0	81
HDPE	31	49	80
PET (bottle grade)	38	39	77
PS (general purpose)	39	48	87

Data for PHA from Gerngross and Slater (2000).
Data for petrochemical polymers from Boustead (1999).

A more recent publication, co-authored by Gerngross and Slater, studies in more detail the greenhouse gas profile of PHA production in genetically modified corn (Kurdikar et al., 2001). While the grain is harvested in a conventional manner, the polymer is extracted from the corn stover. Two alternative energy systems were studied. In one case process energy requirements are covered by natural gas and in the other, biomass energy from the corn stover residue is used as fuel. The publication focuses primarily on the system cradle-to-factory gate but some data on waste management is also provided. This information has been used in Table 2-24 to estimate also greenhouse gas (GHG) emissions for two cradle-to-grave systems. It can be concluded that PHA production with integrated steam and electricity generation based on biomass scores better than conventional PE production in all cases, while the opposite is the case if natural gas is used to provide the PHA production process with steam and electricity[15]. The authors conclude that it is the biomass power and not the renewable feedstock that makes the product preferable to PE from a GHG point of view. On the other hand it is a feature of the biorefinery concept to make best use of all product and co-product streams for material and energy purposes; it is therefore hardly possible to draw an a clear-cut borderline between the production of bioenergy and the bio-based polymer.

Table 2-24: Greenhouse gas emissions from the life cycle of polyhydroxyalkanoates (PHA) and polyethylene (PE) (Kurdikar et al., 2001; complemented with own assumptions)

All values in kg $CO_{2\,eq.}$ / kg polymer	Cradle-to-gate fossil $CO_{2\,eq.}$ (A)	$CO_{2\,eq.}$ uptake in biopolymers 1) (B)	$CO_{2\,eq.}$ uptake in ash 2) (C)	Cradle-to-gate net $CO_{2\,eq.}$ (D) 6)	$CO_{2\,eq.}$ embodied in polymer 3) (E)	Cradle-to-grave $CO_{2\,eq.}$ without energy recovery 4) (F) 7)	Cradle-to-grave $CO_{2\,eq.}$ with energy recovery 4) 5) (G)
PHA, natural gas	ca. 5.8 8)	2.0	-	ca. 3.8	2.0	ca. 5.8	ca. 4.8
PHA, bioenergy	-0.5 9)	2.0	1.5	-4.0	2.0	-2.0	-3.0
PE	1.8	-	-	1.8	3.1	4.9	2.8

1) Uptake of carbon from the atmosphere and fixation in biopolymer.

2) Carbon fixed in the ash from the boiler (due to incomplete combustion).

3) Both fossil and biogeneous CO_2 is accounted for here. For PHA values in column B and E are identical.

4) Waste incineration in a plant without resp. with energy recovery

5) Estimated CO_2 credits for 20% electricity yield from waste-to-energy recovery: 1 kg CO_2/kg PHA, 2.1 kg CO_2/kg PE (underlying assumptions: Efficiency of electricity generation in average power station = 30%; CO_2 emission factor of fuel mix used = 74 kg CO_2/GJ; Heating value, PHA = 18 MJ/kg; Heating value, PE = 42 MJ/kg).

6) (D) = (A) - (B) - (C)

7) (F) = (D) + (E)

8) Including energy use for smaller consumers, i.e. compounding, farming etc.

9) Small fossil energy input minus credit for surplus electricity produced from biomass

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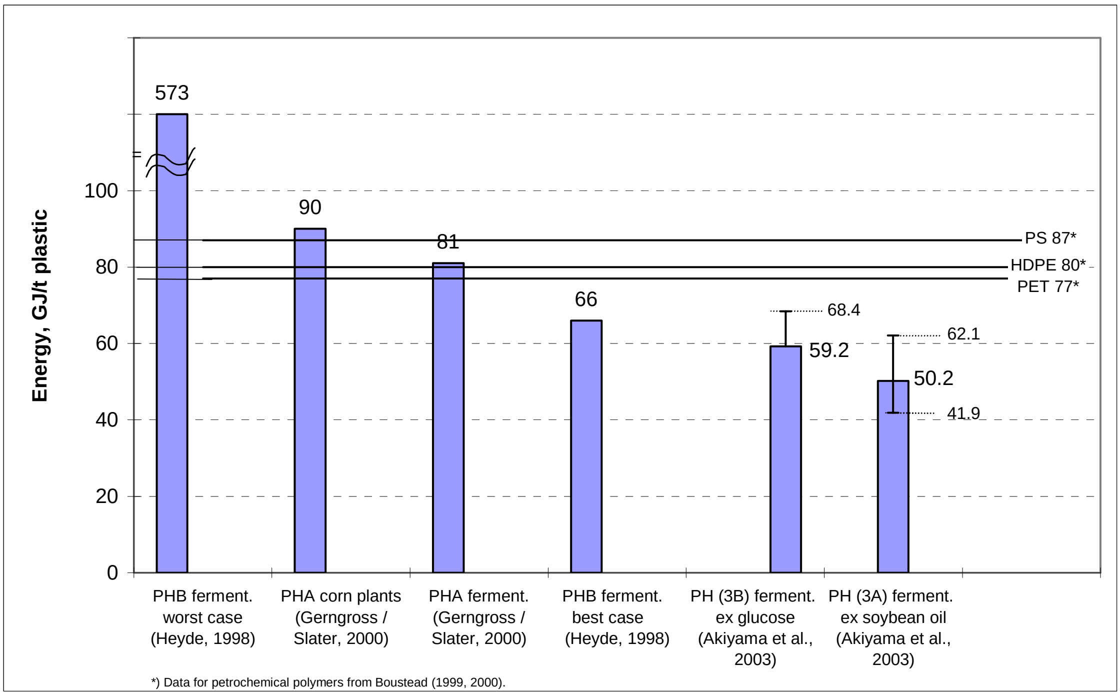
[15] Note that the underlying process energy requirements for "PHA, natural gas" in Table 2-23 is around 100 GJ/t, while the respective value for "PHA grown in corn plants" in Table 2-24 is 90 GJ/t.

Heyde (1998) and Luck (1996) studied PHBs some years ago. Heyde (1998) compared the energy requirements of PHB production by bacterial fermentation using various feedstocks and processes to those of High Density Polyethylene (HDPE) and polystyrene (PS). The PHB options studied include substrate supply from sugar beet, starch, fossil methane and fossil-based methanol and moreover, in the processing stage, the options of enzymatic treatment and solvent extraction. Figure 2-15 shows the energy requirements for PHA production by fermentation according to Heyde and compares them with the results of Gerngross and Slater (see above, Table 2-23) and with Akiyama et al. (see below). An earlier publication by Luck (1996) showed that the choice of waste management process can have a decisive influence on the results. For example, PHB manufactured in an efficient way and disposed of with municipal solid waste (MSW, German average) requires more energy resources and leads to higher GHG emissions than HDPE if the latter is recycled according to the German 1995 Packaging Ordinance (64% material recycling). If, on the other hand, the plastics waste is fed to average municipal solid waste incineration (MSWI) plants in both cases, then the results are comparable for energy and GHG emissions.

Figure 2-15: Cradle-to-factory gate energy requirements for the production of PHAs



*) Data for petrochemical polymers from Boustead (1999, 2000).

Akiyama et al. (2003) have published the most detailed, publicly available environmental analysis on polyhydroxyalkanoates to date (their paper also contains cost estimates, see Section 2.4.6). They distinguish 19 different cases for the production of 5000 t.p.a. of poly(3-hydroxybutyrate-*co*-5mol% 3-hydroxyhexanoate) [P(3HB-*co*-5mol% 3HHx), also referred to as P(3HA)] from soybean oil and of the same amount of poly(3-hydroxybutyrate) [P(3HB)] from glucose. These cases differ with regard to fermentation conditions and fermentation performance and they were calibrated against experimental data. As shown in Figure 2-15 the production of P(3HA) from soybean oil can be realized with lower energy inputs than P(3HB) production from glucose. The main reasons are that a lower amount of soybean oil is used due to higher yields of the fermentation process leading to P(3HA) and because the (cradle-to-gate) energy requirements for soybean oil per unit of weight is also lower than for glucose. These two factors are only partly compensated for by the higher electricity use for the soybean oil-based fermentation process compared to the glucose-based fermentation. Akiyama et al. (2003) have also calculated CO_2 emissions for all the cases studied. To this end they have determined the total CO_2 balance from cradle to factory gate, thereby accounting for both the fossil and the biogenous carbon flows. This was done by firstly calculating the emissions originating from fossil fuels and secondly deducting the CO_2 equivalents embodied in the polymer. While this calculation method is flawless, the results cannot be easily compared to those of most other LCA studies which present only results for the CO_2 emissions from fossil fuels (e.g. Table 2-6).[16] We have therefore added to Akiyama's results, which range between –0.4 and +0.7 kg CO_2/kg PHA, the CO_2 equivalents of the embodied biogeneous carbon and arrive at values in the range of about 2.5 to 3.5 kg CO_2/kg PHA for all the 19 cases. These values can be compared to those for starch polymers which lie in the range of 1.1 to 3.6 kg CO_2/kg polymer (see Table 2-6, second column from the right). These values translate into emission savings of 1.2 to 3.7 kg CO_2/kg polymer compared to conventional polyolefins (see Table 2-6, first column from the right). If polyolefins are used as benchmark also for PHA, the emission savings are hence estimated at 1.3 to 2.3 kg CO_2/kg polymer (equivalent to savings of 27-48% compared to polyolefins).

As the comparison of the various studies shows, the CO_2 emissions reported for PHAs differ widely. While the higher values reported are larger than those for petrochemical polymers, there also seems large scope for improvement. PHA production both by bacterial fermentation or in plants is in an early stage of development compared to not only petrochemical polymers but also other bio-based polymers; efficiency gains are therefore likely to accrue from technological progress and upscaling of production. The fact that PHA prices (see Section 2.4.6) are now clearly beyond those for other bio-based polymers is a consequence of the low yields and efficiencies. Since these drawbacks need to be overcome as a prerequisite for a wide commercial success, the large-scale production of PHAs can be expected to be accompanied by environmental impacts that are on the lower side of those shown in Figure 2-15.

2.5 Bio-based polyurethane PUR

Polyurethanes (PURs), the family of polymers which have recurring urethane [-NH-CO-O] groups in the main chain, were introduced commercially in 1954. They are extremely versatile plastics available in a variety of forms ranging from flexible or rigid foams, solid elastomers, coatings, adhesives and sealants (SPI, 2003). For this reason PURs occupy an important position in the world market of high performance synthetic polymers (Vilar, 2002). World consumption of PURs was in the order of 8 million tonnes in 2000 and the forecasted consumption for the medium term is rather high with growth rates of around 6% p.a. Today, PURs occupy the sixth position (about 5% of total consumption) in the market for the most widely sold plastics in the world (Vilar, 2002).

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[16] Basically both approaches are correct if they are interpreted correctly: while the approach taken by Akiyama et al. (2003) represents an impeccable method for calculating the overall emissions balance for a cradle-to-factory gate system, the latter approach is suitable to gain insight into the total life-cycle emissions including the release of CO_2 from the embodied carbon.

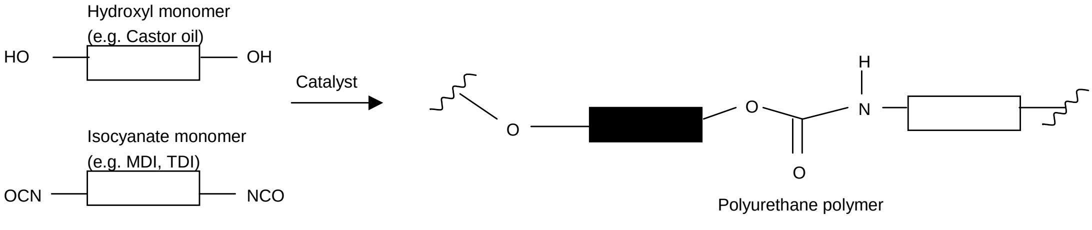
PURs are prepared by reacting two components: a polyol and an isocyanate. While the isocyante component is always derived from petrochemical feedstocks, the polyol component has the potential to be bio-based in some applications. Vegetable-oil based polyols are possible from crops such as castor bean, rapeseed and *Euphorbia lagascae* (Clark, 2001), soy bean (Mapelston, 2003), sunflower (Schmidt and Langer, 2002) and linseed. Castor oil, derived from the castor bean, already has some importance as a PUR feedstock but it yields resins with limited hardness and other mechanical properties. Most other vegetable oil-based polyols do not have the necessary functionality (hydroxyl groups) in their native form to be useful for PUR manufacture so this needs first to be introduced by chemical manipulation (Clark, 2001), significantly increasing production costs. Polyester polyols - another class of polyol - may also be partially bio-based; for example the di- or triacid component could be a fermentation product such as succinic or adipic acid and the diol component could be 1,4-butanediol or glycerol. Polyester polyols are not yet economically viable due to high raw material and processing costs associated with the bio-based feedstock; however as discussed in other sections, there is good potential for this situation to change over the next few years with advances in fermentation technology.

Since PUR chemistry is wide-ranging in terms of both feedstock possibilities and applications, this section will endeavour only to present the technology basis, possible bio-based feedstocks in PUR production, and a qualitative appraisal of the possible market size and share of bio-based PURs. The flexible foam product of Metzeler Schaum GmbH, Germany, which uses a polyol derived from sunflower oil, will be used as a case study.

2.5.1 Production of bio-based PUR

PURs are produced by the polyaddition reaction of an isocyanate, which may be di- or polyfunctional, with a diol or polyol (an alcohol with more than two reactive hydroxyl groups per molecule), resulting in the formation of linear, branched, or cross-linked polymers (Figure 2-16) (Dieterich, 1997). Other low molecular weight reagents such as chain extenders or crosslinking agents (also containing two or more reactive groups) may be added during the polyaddition process, as may additives such as catalysts, blowing agents, surfactants, and fillers.

Figure 2-16: Generic process for PUR production from a polyol and an isocyante (Dieterich, 1997)



PUR feedstocks and possibilities for bio-based monomers

In the PUR system, the isocyanate component can be aromatic or aliphatic. Commonly used isocyanates for manufacturing polyurethanes are toluene diisocyanate (TDI) [$CH_3C_6H_3(NCO)_2$], methylene diphenyl isocyanate (MDI) [$OCNC_6H_4CH_2C_6H_4NCO$], and polymeric isocyanates (PMDI) (SPI, 2003). TDI and MDI may be prepared from accessible low cost diamines, and as such constitute 95% of total consumed isocyanates (Vilar, 2002).

Polyols can be polyesters, polyethers or hydrocarbons. As shown in Table 2-25, the more heavily consumed polyols are polyethers of various structures (poly(propylene oxide) glycols etc.). Polyesters are the next most important group: at about one third of the volume of polyethers, this still amounts to a consumption of more than 1 million tonnes per year (Vilar, 2002).

Table 2-25: World consumption of polyols and isocyanates in thousands of tonnes per year (Vilar, 2002)[1]

Year	**2000**	**2002**	**2004**
Polyether polyol	3465	3880	4350
Polyesther polyol	1180	1330	1490
MDI	2370	2650	2970
TDI	1441	1610	1800
Total	8460	9470	10610

[1] Figures for polyethers and polyester polyols also include all the chain extenders and other additives used in the formulation of the different PUR systems.

While it seems unlikely that the isocyanate component will be produced from a bio-based feedstock (Metzeler, 2003), there are a number of possibilities for the polyol to be bio-based (Table 2-26).

Table 2-26: Bio-based polyols for PUR production [1,2,3,4]

Polyether polyol	**Initiators**: glycerine, sucrose, glucose, fructose, water
Polyester polyol	**Diacids**: azelaic acid, dimer acid, adipic acid, succinic acid, glutaric acid **Di or tri-functional polyols**: 1,10-dodecanediol; 1,6-hexanediol, 1,12-hydroxystearyl alcohol, dimerdiol, ethylene glycol, 1,2-propanediol, 1,4-butanediol, glycerol.
Plant oil based (oleochemical)	Castor oil (ricinoleic acid) & derivatives Rapeseed oil (oleic acid) derivatives Eurphorbia oil (vernolic acid) derivatives Soybean oil derivatives

[1] Höfer (2003),

[2] Mapelston, (2003a),

[3] Liu (2000),

[4] Vilar (2002)

Polyols based on castor oil and other plant oils

Castor oil, derived from the bean of the castor plant, contains 87-90% ricinoleic acid (12-hydroxyoleic acid) which is a fatty acid triglyceride (Figure 2-17). High purity castor oil may be used as a polyol to produce PUR coatings, adhesives, and casting compounds (Vilar, 2002). Castor oil can be transesterified with a polyhydroxylated compound such as glycerine to obtain higher hydroxyl functionality (more –OH groups for a given molecular weight) (Figure 2-18). In this way, the range of uses for castor oil in PUR systems is broadened e.g. this allows more applications in rigid foams.

Figure 2-17: Common plant oils (polyols and polyol precursors) (Clark, 2001)

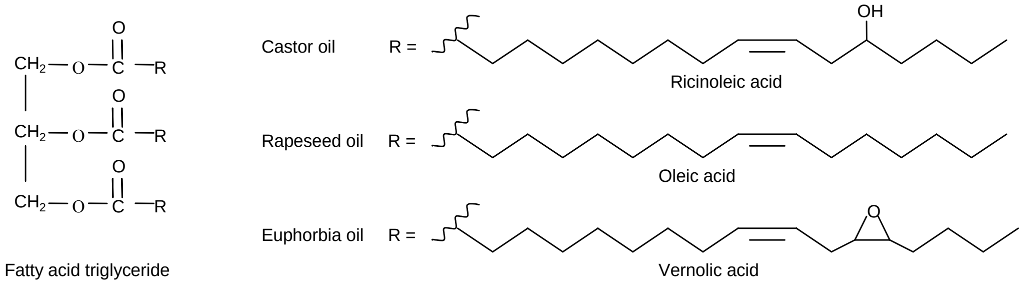
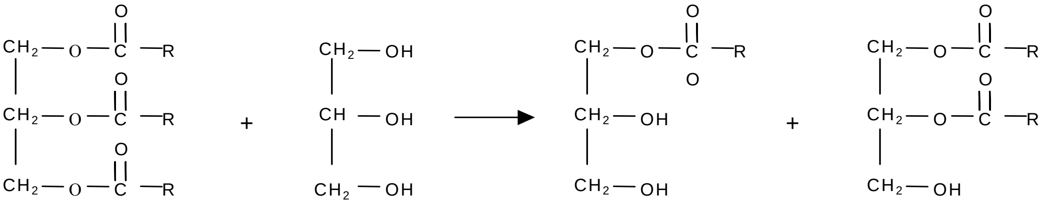
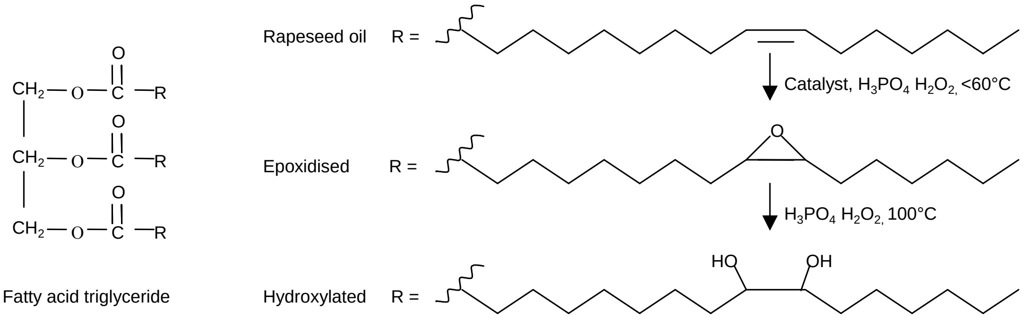


Figure 2-18: Transesterification of castor oil with glycerine to produce a mixture of polyols with higher functionality (Vilar, 2002)



The use of other oilseeds in PURs has been studied by Clark (2001). By sequential epoxidation (i.e. the action of hydrogen peroxide on double bonds to incorporate reactive oxygen in the molecular structure) and ring opening (acidification resulting in the formation of –OH groups), an appropriate degree of hydroxylation may be incorporated into polyols derived from (e.g.) rapeseed (Figure 2-19). Polymers derived from rapeseed have higher thermal stability and reduced degradability compared to their castor oil derived counterparts. However, there is still a problem of high expense associated with the chemical manipulation steps. Whereas rapeseed requires two chemical manipulation steps, Euphorbia lagascae oil has a reasonably high level of functionalisation and requires only one chemical manipulation – the ring opening step, which is by far the least costly of the two steps. This makes euphorbia potentially much more attractive than rapeseed or linseed, assuming final material properties are comparable (Clark, 2001). By varying a large number of conditions, a range of feedstocks based on these plant-derived polyols with different degrees of flexibility and hydroxyl content may be prepared and reacted with different isocyanides (TDI and MDI) to produce PURs including rigid foams for packaging/pipe insulation, other rigid PURs and flexible elastomers (Clark, 2001).

Figure 2-19: Epoxidisation and ring opening of plant oil to obtain a polyol (Clark, 2001)



Polyester polyols with a bio-based component

Polyester polyols were the first polyols used in the beginning of PUR development, and may be produced by polycondensation of di- and trifunctional polyols with dicarboxylic acids or their anhydrides. Options for bio-based polyols include ethylene glycol, 1,2-propanediol, 1,4-butanediol, 1,6-hexanediol and glycerol. Dicarboxylic acids or their anhydrides include bio-based succinic acid, adipic acid and dimer acid (Vilar, 2002).

Relatively low cost polyester polyols may also be based on recovery materials. Mixed adipic, glutaric and succinic acid polyesters are made using purified nylon waste acids (AGS acids). AGS acids are also hydrogenated to make a mixture of 1,4-butanediol, 1,5-pentanediol and 1,6-hexane diol, which is used to make polyadipates having a low melting point. Mixed polyadipates from hydrogenated AGS acids are used to make microcellular elastomers with good hydrolytic stability (Vilar, 2002). This is important to note in that any bio-based polyol must also compete on cost and environmental impact basis with such waste streams.

Chain extenders

Low molecular mass polyols (e.g. 1,4-butanediol), in contrast to the higher molecular mass polyols mentioned above, are chiefly used as "chain extenders". In the production of PUR elastomers they are generally used in the synthesis of the "hard" segment (Dieterich, 1997).

Example of a bio-based PUR process

In the Metzeler Schaum process to produce PUR flexible foam (Palz et al., 2003), a sunflower oil-based polyol is used. Triglyceride fatty acid from sunflower oil is first hydroxylated via epoxidisation and ring opening in a similar process to that shown in Figure 2-19. The polyol and an isocynanante (TDI or MDI) are dispensed with water onto a conveyor belt. There, they react in the presence of a catalyst. Two main reactions occur simultaneously: the isocyanate reacts with the polyol to form PUR; and the isocyanate reacts with water to form polyurea with the evolution of carbon dioxide; which acts as the blowing agent in foam production (Vilar, 2002). The resulting block foam is cooled down for 48 hours then cut into the finished product shape (in this case, mattresses). The product contains 25% sunflower oil on a weight/weight basis (Metzeler, 2003). The total production amounts to about 1,000 tonnes per year, which is equivalent to a yearly consumption of 240 tonnes of sunflower oil (270 tonnes of sunflower-oil based polyol) (Palz et al., 2001).

2.5.2 Properties

The physical and chemical properties of PURs vary over a wide range, depending on the constituent monomers and reaction conditions. Properties of the various forms of PURs are discussed in relation to the application areas in Section 2.5.4.

In comparison with polyether polyols based PURs, the polyester based PURs are more resistant to oil, grease, solvents and oxidation. They possess better properties related to tension and tear strength, flex fatigue, abrasion, adhesion and dimensional stability. On the other hand, polyester based PURs are more sensitive to hydrolysis and microbiological attack. The attractive mechanical properties of polyester based PURs can be explained by the greater compatibility between polar polyester flexible segments and polar rigid segments, resulting in better distributed small crystalline rigid blocks (Vilar, 2002). The use of longer chain polyols in the production of polyester polyols results in PURs with greater flexibility and hydrolytic stability and reduced polarity and glass transition temperature (Vilar, 2002).

Although most PURs are thermosets, some grades of PUR elastomers are thermoplastic in nature and can be moulded, extruded and calendered (SPI, 2003).

2.5.3 Technical substitution potential

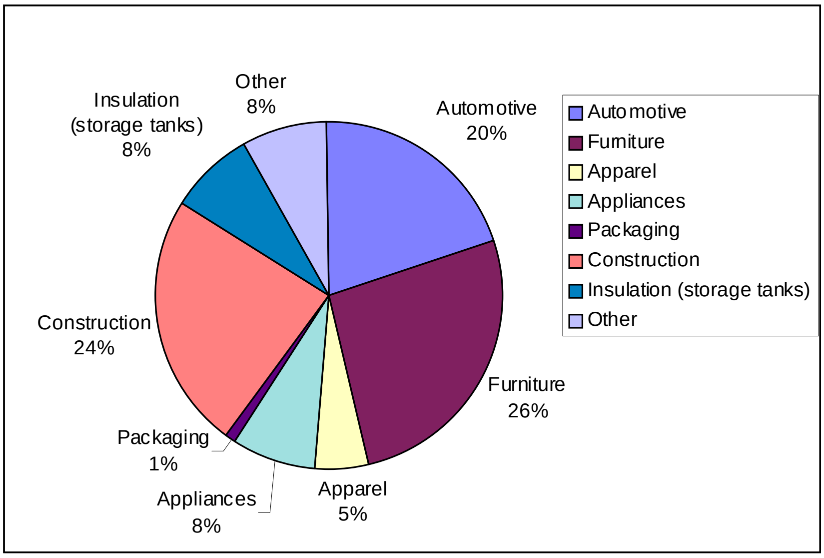
For a bio-based PUR to substitute for its conventional petrochemical-derived equivalent, the bio-based product must be seen as a good product in its own right; thus meeting all processability and in-use requirements. As an example of where public perception can influence the course of substitution (also market acceptance of the product), consumers often associate bio-based with biodegradable. This is generally not the case for PURs, although some bio-derived components (e.g. plant-derived polyols containing carboxyl groups) do result in more easily biodegraded products. This may lead to the false impression that a PUR with a bio-based component is less durable than the 100% petrochemical-derived equivalent (Metzeler, 2003).

As new applications for PUR are still emerging with the material substituting for other materials, and performance improvements are being achieved in automotive seating, furniture and footwear due to remodeling of PUR morphology (Mapelston, 2003a), it may be concluded that there is also some potential for bio-based PURs to substitute for other materials.

2.5.4 Applications today and tomorrow

PUR is now almost exclusively produced from petrochemical feedstocks. Due to its wide spectrum of types and properties (soft and flexible foams, coatings, elastomers and fibres) PUR is being used in a very wide range of applications (see Figure 2-20). While the application area of construction and insulation seems rather difficult to access by bio-based polyurethanes since price competition is fierce, the other sectors may offer more opprtunities for the short to medium term.

Figure 2-20: Main applications for PUR by market sector (scope: EU 15, values for 1999;weight-%)



Today, the market for bio-based PURs is small and premium applications are being targeted. As an example, Metzeler Schaum currently produces only one bio-based product for one market: the Rubex Nawaro® mattress for the furniture market. According to Metzeler (2003), this application currently represents about 1% of the PUR market in the EU. In the future, the company sees potential for its bio-based flexible foam product to enter other markets including, as percentage of the company's total production of bio-based PUR: 5% in agriculture; 20% in transportation (e.g. automobile seats); and 5% in houseware (e.g. sponges) (Table 2-27). The interest of car manufacturers in bio-based polymers in general (e.g. Toyota, see Section 2.2.4) supports the rather high expectation set in transportation as a new outlet for bio-based polyurethanes.

Table 2-27: Main applications for flexible bio-based PUR-foams produced by Metzeler Schaum according to market sector[1] (scope: EU 15)

Sector	% of production today	% of production in 2020
Packaging	0%	
Building	0%	5%
Agriculture	0%	
Transportation	0%	20%
Furniture	100%	70%
Electrical appliances and electronics (E&E)	0%	
Houseware	0%	
Others	0%	5%
total for all market sectors	100%	

[1] Metzeler (2003).

Some of the many possible options for monomers and chain extenders from renewable feedstocks are given in Table 2-28. Note that volumes of these formulations were not available so it is somewhat difficult to judge whether the different feedstocks represent a minor or a major contribution to the total PUR market.

Taking a broader look at (current) application areas for PURs, it should be noted that by combining different raw materials such as polyols, isocyanates and additives, it is possible to obtain countless varieties of foam products, as well as a multitude of other (non-foam) materials. Today, PURs such as flexible and rigid foams, coatings, elastomers, fibers, etc. comprise about 20 kg of the bulk of passenger cars (Vilar, 2002). Although the fields of PUR applications are diverse, several key segments may be identified (Figure 2-21), of which furniture (26%), construction (24%) and automotive (20%) together constitute 70% of the total market in EU-15 countries

Table 2-28: PUR formulations with a bio-based component and main applications [1,2,3,4]

Type 1: Oleochemical polyols, hydroxy functionalised derivatives thereof.
Type 2: Other polyol with one or more bio-based components.
Type 3: Other bio-based.

Class of raw material	Type of PUR formulation & main applications
Type 1: Hydroxy-functional oils (natural oils – fatty acid trigylcerides; derivatives thereof)	2 pack systems, aqueous drying industrial coatings; casting resins, rubber and fibre binders, adhesives. Derivatives have superior hydrolytic stability against alkali and acids, high chemical resistance against corrosives, improved mechanical properties.
Type 1: High molecular weight diacids and polyester derivatives	Aqueous PUR dispersions, laminating, adhesives
Type 1: High molecular weight diols	Aqueous PUR dispersions, casting, adhesives, thermoplastic polyurethanes (TPUs), building blocks for soft segments in TPUs
Type 1: Derivatives of other plant-based substances	Plant components act as 'hard' segments (higher crosslinking density)
Type 2: Low molecular weight diacids and polyester derivatives	Used in the synthesis of the 'hard' segment in thermoplastic polyester-urethanes. Biodegradability enhancer.
Type 2: Low molecular weight diols	Chain extender in the synthesis of the 'hard' segment. Some types (eg glycerol) introduce a small, defined degree of branching
Type 3: Natural Fibres	PUR resin sprayed onto preforms of natural fibres for low density door panels for autos.

[1] Höfer (2003),
[2] Mapelston, (2003a),
[3] Liu (2000);
[4] (Vilar, 2002).

PURs from castor oil and its derivatives are used with excellent hydrolytic stability, shock absorbing and electrical insulation properties. They also have been found to be very useful in the preparation of flexible, semi-rigid and rigid PU foams, resistant to moisture, shock absorbing, and with low temperature flexibility (Vilar, 2002).

2.5.5 Current and emerging producers

Metzeler Schaum GmbH of Memmingen, Germany is a major producer of flexible PUR foam. Over the last few years the company has developed a slabstock foam product incorporating a bio-based feedstock: the Rubex Nawaro® mattress which is produced using a polyol derived from sunflower oil (Schmidt and Langer, 2002) (see also section 2.5.1). The company undertook R&D and is now on the verge of commercialising the product, albiet on a relatively small scale. The Rubex Nawaro® production line employs 11 full time personnel and was started up in September 2001. In 2002, 30,000 units of mattress were produced; and the target for 2003 is to reach capacity production of 60,000 units (Metzeler, 2003).

According to Metzeler Schaum, it is critically important that consistent quality is achieved with the polyol; otherwise there will be a high scrap rate from the conversion of PUR (the company has achieved targets in this regard). The market expectation is basically that any variations in quality of the bio-based raw material be in the same (narrow) range as for the synthetic equivalent. In the future, the company could potentially utilise other bio-based polyols for its flexible foam products if market interest is there. While there is scope for sourcing raw materials in new EU member states in the next few years, German farmers are also looking for new markets for their products. In addition, the customer who chooses to purchase the bio-based product at a higher price than the market average is generally aware of environmental and social aspects related to the product and is interested in knowing where the raw material is sourced, with local sourcing being the preference (Metzeler, 2003). The company does not envisage selling the Rubex Nawaro® mattress outside Germany for some years, thus the product clearly falls in the niche category at present (as for many other bio-based polymers).

A few more companies/consortia have been identified which are active in the field of bio-based PUR:

- The U.S. company Urethane Soy Systems Company (Princeton, Illinois) is producing a polyol (tradename: SoyOyl) which polyol is being used in the manufacture of Biobalance, a new polymer recently introduced by the Dow Chemical Company for use in commercial carpet backing (ASA, 2003).
- Polyols produced by Urethane Soy Systems Company are also being used to produce rigid PUR foam (Mapelston, 2003).
- The Ford company presented their environmental friendly concept vehicle (named Model U) in which several bio-based polymers are being used, among them bio-based PUR for seating foam (Mateja and Tribune, 2003).

2.5.6 Expected developments in cost structure and selling price

Selling price

The market price for petrochemical PURs is in the range of €4.40 - 4.70 per kg for ester-types and €5.20 - €5.40 for ether types (Plasticsnews, 2003).

Metzeler Schaum (Metzeler, 2003) expect that their bio-based PUR product will be commercially viable, even at a higher price than its petrochemical-based equivalent. However, this will only be possible in niche markets where environmental or other credentials of the bio-based product justify the price differential. Market breakthroughs in terms of bulk volumes are only likely to flow on from significant reductions in the cost of bio-based feedstocks.

Expected price developments

It is expected that in niche markets, the price of bio-based PURs will always be higher than conventional equivalents due both to the smaller scale of production and the high cost associated with using the renewable feedstock. Sales will thus be dependent on pro-active consumer choice for the bio-based product. In bulk markets, bio-based PURs will need to be introduced with price (and quality) on par with conventional equivalents. According to the U.S. United Soybean Board, the "demand for polyols has reached 3 billion pounds of which 800 million pounds can be made with the more cost-effective soybean oil". This is equivalent to a total market potential in North America of about 25% (Anon, 2003.

2.5.7 Environmental impacts

No information is available about the environmental impacts of bio-based PUR in relation to conventional petrochemical-based equivalents.

The U.S. National Institute of Standards and Technology (NIST) has completed work on life cycle inventories for two new soy polyols. To date, only aggregated results using a single score indicator[17] have been published in the United Soybean Board newsletter (USB Weekly, 2003). The soy polyols shows only about **one quarter** the level of total environmental impacts with significant reductions in fossil fuel depletion (by about a factor of six), global warming, smog formation and ecological toxicity.

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[17] A single-score indicator is an overall score that is determined by weighting individual results for the various impact categories. The single-score indicator discussed in USB Weekly (2003) comprises the following impact categories: acidification, "critical air pollutants", ecological toxicity, eutrophication, fossil fuel depletion, global warming, habitat alteration, human health, "indoor air", ozone depletion, smog and water intake. It should be noted that weighting factors are always related to a value system ("value-laden") and are therefore not an input that can be determined in an objective manner.

The source just quoted does not specify the chemical composition of the polyol and it is also unclear to which extent savings at the level of the polyol would translate to benefits at the level of polyurethanes. We have therefore conducted independent back-of-envelope calculations assuming that the environmental impact of the diol would be comparable to that of 1,3-propanediol. It needs to be emphasized that this is a very rough approach since low molecular mass polyols are actually used as chain extenders (see above). The following benefits have been determined:

- The energy savings for the bio-based polyol as opposed to the petrochemical polyol amount to 45-60% (depending on the value chosen for the petrochemical polyol). While this saving potential is below the value reported in USB Weekly (2003), it is nevertheless substantial.
- The energy savings for the bio-based PUR relative to the petrochemical PUR has been estimated at around 20% for rigid PUR and ca. 40% for flexible PUR (the savings are higher for flexible PUR due to the larger share of polyols).

As explained in Section 2.5.1 numerous different types of bio-based polyols can be used for PUR production, resulting in a wide range of products. It is therefore not astonishing if the environmental assessment of bio-based PUR also yields a rather wide range of values. The results discussed above give a first indication of this range. To obtain a better understanding of the total saving potential related to PUR, a more systematic analysis would be required which should be based on on a preselection of polyols with a (potentially) favourable environmental profile and a (potentially) large market.

2.6 Emerging technologies: bio-based polyamides (nylon)

Nylon is a generic name for a family of long-chain polyamide engineering thermoplastics which have recurring amide groups [-CO-NH-] as an integral part of the main polymer chain. The nylon fibre industry made a huge impact when it flooded the market in 1939 with the ubiquitous nylon stocking: 64 million pairs were sold, and to this day, most people still associate nylon with fibers. Although use as a fiber dominated the interest in nylon from the outset, the use of nylons as compounds that can be moulded and extruded or otherwise processed like plastics has steadily increased versus that of fibers; in Western Europe from 24 % of total consumption in 1978 to 47 % (of 320,000 t.p.a.) in 1988 (Kohan, 1997). Typical applications for nylon compounds are in automotive parts, electrical and electronic uses, and packaging (SPI, 2003).

Production routes to polyamides via a bio-based intermediate may be identified for nylon 66 (ZWA, 2003), nylon 69 (Höfer, 2003) and nylon 6 (Nossin and Bruggink, 2002). It is understood that these technologies are not currently on the pathway to commercialisation due to the prohibitively high cost of production relative to conventional petrochemical-based equivalents. To illustrate: while DSM has studied a bio-based route to nylon 6, this effort did not move past the research stage due at least partly to the fact that DSM has recently implemented a cheaper petrochemical route to nylon 6, effectively raising the hurdle (i.e. the difference in cost price of the bio-based monomer and the petrochemical-based monomer) for the bio-based route (DSM, 2003). However, applying the same reasoning as for the polyesters PTT, PBT, PBS and so on, given the current pace of technological development in areas such as molecular engineering it is difficult to judge the extent to which bio-based routes to monomers used in the production of polyamides could become economically feasible. Therefore, this chapter will attempt only to give examples of bio-based routes and place them in the context of conventional polyamide applications and market presence.

2.6.1 Production of bio-based polyamides

Polyamides are generally synthesized from diamines and dibasic (dicarboxylic) acids, amino acids or lactams. Where two types of reactive monomer are required, the polymerization is said to be an AABB type; where one suffices, an AB type. A and B stand for the functional groups –NH2 and –COOH, respectively (Kohan, 1997). The different polyamide (PA) types are identified by numbers denoting the number of carbon atoms in the monomers (diamine first for the AABB type). Commercial nylons include (SPI, 2003):

- nylon 4 (polypyrrolidone)-a polymer of 2-pyrrolidone [$CH_2CH_2CH_2C(O)NH$];
- nylon 6 (polycaprolactam)-made by the polycondensation of caprolactam [$CH_2(CH_2)_4NHCO$];
- nylon 66 (polyhexamethylene adipamide) - made by condensing hexamethylenediamine [$H_2N(CH_2)_6NH_2$] with adipic acid [$COOH(CH_2)_4COOH$];
- nylon 69 (polyhexamethylene azelaamide) - made by condensing hexamethylenediamine [$H_2N(CH_2)_6NH_2$] with azelaic acid [$COOH(CH_2)_7COOH$];
- nylon 610-made by condensing hexamethylenediamine with sebacic acid [$COOH(CH_2)_8COOH$];
- nylon 6/12-made from hexamethylenediamine and a 12-carbon dibasic acid;
- nylon 11-produced by polycondensation of the monomer 11-amino-undecanoic acid [$NH_2CH_2(CH_2)_9COOH$];
- nylon 12-made by the polymerization of laurolactam [$CH_2(CH_2)_{10}CO$] or cyclododecalactam, with 11 methylene units between the linking -NH-co- groups in the polymer chain.

To our knowlegde no bio-based polyamides are commercially produced now. Three examples of bio-based monomers for production of PA 6, PA 66 and PA 9T are considered below.

2.6.1.1 PA 66 from bio-based adipic acid

In the bio-based route to adipic acid (Conventional route Figure 2-21; bioroute Figure 2-22), *E. coli* bacteria sequentially ferment to 3-dehydroxyshikimate, then to cis, cis-muconic acid. The final hydrogenation step to adipic acid takes place at elevated pressure. Production of nylon 66 from adipic acid and diamine follows in a conventional step polymerization by means of a carbonyl addition/elimination reaction (Figure 2-23) (UR, 2003).

Figure 2-21: Conventional route to adipic acid (ZWA, 2000)

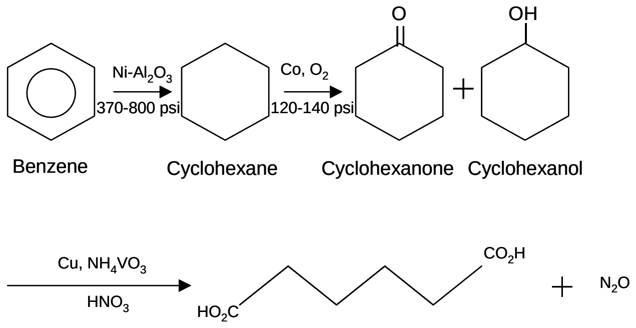


Figure 2-22: Biotechnological production of adipic acid (ZWA, 2000)

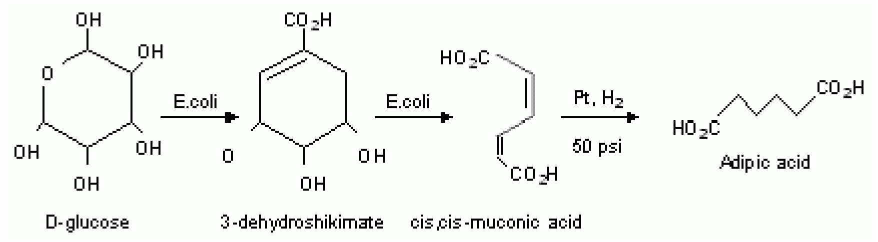
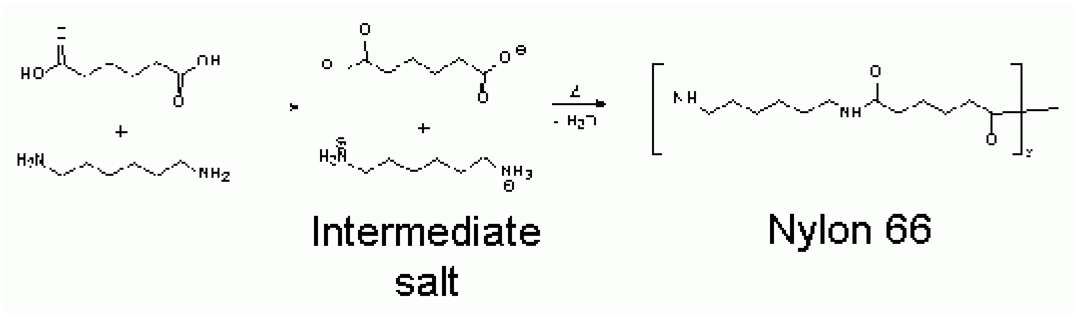


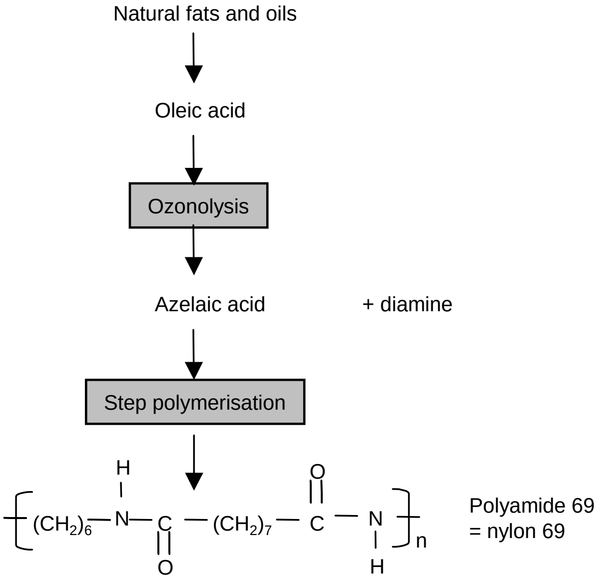
Figure 2-23: Nylon 66 from adipic acid and diamine: conventional step polymerization route by means of the carbonyl addition/elimination reaction (UR, 2003)



2.6.1.2 PA 69 from bio-based azelaic acid

In contrast to the fermentation pathway to adipic acid from glucose, azelaic acid (nonanedioic acid), the diacid monomer for PA69, is produced by a chemical synthesis pathway from oleic acid. Oleic acid is a monounsaturated 18-carbon fatty acid which is found in most animal fats and vegetable oils (e.g. rapeseed oil, see Section 2.5.1, Figure 2-17). Azelaic acid used to be prepared by oxidation of oleic acid with potassium permanganate, but is now produced by oxidative cleavage of oleic acid with chromic acid or by ozonolysis. (see Figure 2-24; Cyberlipid, 2003).

Figure 2-24: Production of azelaic acid and conventional step polymerization to nylon 69 (standard route incorporating the renewable feedstock oleic acid) (Höfer, 2003).

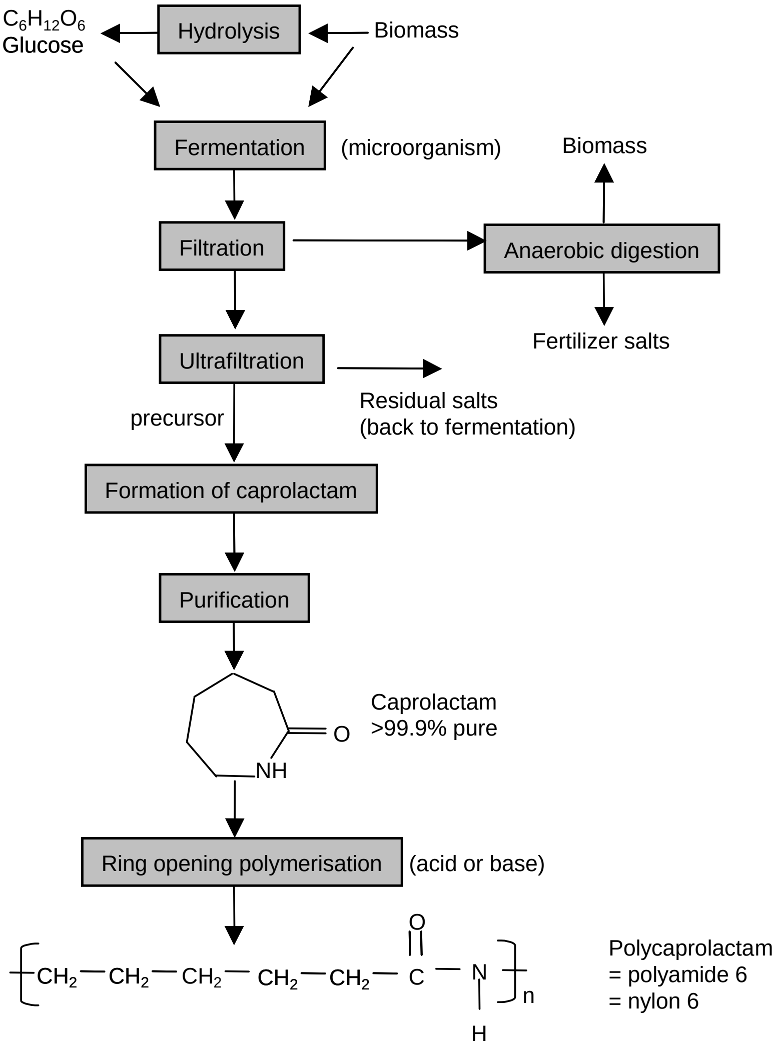


The polymerisation step from azelaic acid and diamine to PA 69 is a conventional step polymerization much the same as that for PA 66, with differences being due to different melt viscosities and melting points (Kohan, 1997). Production of another polyamide, PA 669, from azelaic acid is also mentioned by Höfer (2003).

2.6.1.3 PA 6 from bio-based caprolactam

Caprolactam, the monomer for nylon 6, may be produced fermentatively from glucose (in the future; other fermentable sugars from biomass) via an unspecified intermediate (Figure 2-25) (Nossin and Bruggink, 2002). Nylon 6 follows from the ring opening polymerisation of caprolactam.

Figure 2-25: Biotechnological production of caprolactam and nylon 6 via conventional ring opening polymerisation (Nossin and Bruggink, 2002)



Potential future bio-based feedstocks

Table 2-29 lists a number of monomers which are currently produced or have the potential to be produced from a bio-based feedstock. The most important of these in volume terms are adipic acid and ε-caprolactam for the production of nylon 66 and nylon 6 respectively, the processes for which have been described above.

Table 2-29: Bio-based monomers for the production of polyamides (adapted from Kohan, 1997).

Monomer for polyamide	x or y *	Conventional source	Bio source
Adipic acid (hexanedioic acid)	6	benzene, toluene	glucose
Azelaic acid (nonanedioic acid)	9	oleic acid	oleic acid
Sebacic acid (decanedioic acid)	10	castor oil	castor oil
Dimer acid (fatty acids, dimers)	36	oleic and linoleic acids	oleic and linoleic acids
11-Aminoundecanoic acid	11	castor oil	castor oil
ε-caprolactam	6	benzene, toluene	glucose

* x, y = number of carbon atoms due to monomer in polyamide

2.6.2 Properties

The utility of nylons is based on their combination of properties and on their susceptibility to modification. Key properties are resistance to oils and solvents; toughness; fatigue and abrasion resistance; low friction and creep; stability at elevated temperatures; fire resistance; drawability; good appearance and good processability (Kohan, 1997).

Nylons 6 and 66 are used where toughness and thermal resistance are required at moderate cost. Disadvantages are relatively high water absorption and poor dimensional stability. To solve this problem and to lower cost, nylons are frequently glass reinforced. Other nylons useful as engineering plastics are nylons 69, 610, 612, 11, and 12. These products have reduced moisture absorption and better dimensional stability. However, these forms of nylon have poorer toughness and temperature resistance; properties that deteriorate even further when the resins eventually do absorb moisture (Nexant, 2002).

2.6.3 Technical substitution potential

Bio-based nylons have theoretically 100% substitution potential for their petrochemical equivalents. Substitution potentials (of either bio-based or petrochemical based nylons) for other materials are not known but are assumed to be close to zero.

In terms of cross substitution, the amount of PA 66 used relative to that of PA 6 has increased over time. Consumption (PA 6/66/other) for Western Europe, Japan, and the United States was in the ratio 48/41/11 for 1978 and 1983, 44/46/10 for 1988 (Kohan, 1997).

2.6.4 Applications today and tomorrow

To our knowledge, nylons are now exclusively produced from petrochemical feedstocks (there may be some exceptions for specialties with very small production volumes). Nylons are used in many and diverse ways. They are found in appliances, business equipment, consumer products, electrical/electronic devices, furniture, hardware, machinery, packaging, and transportation. This diversity makes classification and analysis difficult as shown in Table 2-30 which shows the pattern of consumption in Western Europe.

Table 2-30: Main applications for polyamides by market sector -Estimate for Western Europe

Processing/application	Market share
Injection moulding	**46%**
Automotive industry	17%
Electrical	13%
Machinery	4%
Furniture, household	4%
Building	4%
Other	3%
Extrusion	**14%**
Film	7%
Semi-finished goods	3%
Monofilaments	2%
Other	1%
Blow moulding, cast PA, fluidized bed coating	**2%**
Fibres	**38%**
Total	**100%**

Note: The share of the fibre market has been estimated using data for Germany in 1995 (estimated based on a variety of sources); the market shares of all other applications were calculated using the shares for the non-fibre markets in Western Europe in 1991 (PlastEurope).

2.6.5 Current and emerging producers

To our knowledge, bio-based nylons are now not being produced in meaningful quantities. No announcements about larger investments have so far been made for nylons. However, major producers of polyamides, e.g. DuPont and DSM are or have been involved in research into bio-based monomers for polyamides. They are generally held back by the as yet prohibitive price of the bio-based raw materials and by the insufficient performance of the biotechnological conversion steps.

2.6.6 Expected developments in cost structure and selling price

For the identified production routes to polyamides via a bio-based intermediate production costs are still prohibitively high relative to conventional petrochemical-based equivalents. To illustrate: Based on a feasibility study DSM came to the conclusion that the bio-based route to nylon 6 would allow the production of competitively priced caprolactam (Nossin and Bruggink, 2002). However, the company subsequently switched to a cheaper petrochemical-derived feedstock as a precursor to nylon 6. This effectively raised the hurdle (i.e. the difference in cost price of the bio-based versus the petrochemical-based monomer) for the bio-based route (DSM, 2003).
This is not the end of the story, since it is expected that at some time in the future fermentable sugars will become cheaper and microorganisms will be engineered for high yield so that a large-scale process becomes financially viable. Targets quoted by DSM to achieve a lower cost price for bio-based caprolactam are (Nossin and Bruggink, 2002): price of fermentable sugars below € 75 per tonne in 2010 (equating to an approximately 50% reduction compared with the 2002 price); annual production capacity of 100,000 tonnes per year; and no penalties associated with waste streams.

2.6.7 Environmental aspects

The production of petrochemical nylons is known to be up to two to three times more energy intensive than the manufacture of petrochemical bulk polymers such as polyethylene, polystyrene or polyethylene terephthalate (compare Table 2-11; see also Boustead 1999/2002 and Patel, 2003). This has mainly to do with the large number of conversion steps and partly with the production of lower-value byproducts (e.g. ammonium sulphate as a byproduct of hydroxylamine sulphate in the nylon 6 chain). If the use of bio-based feedstocks can be combined with new routes characterised by shorter process chains and higher yields, this will nearly certainly allow to reduce the overall energy input and the attendant environmental impacts. Both the biotechnological and the conventional chemical conversion of bio-based feedstocks seem to offer interesting possibilities to reach these goals (see Section 2.6.1).

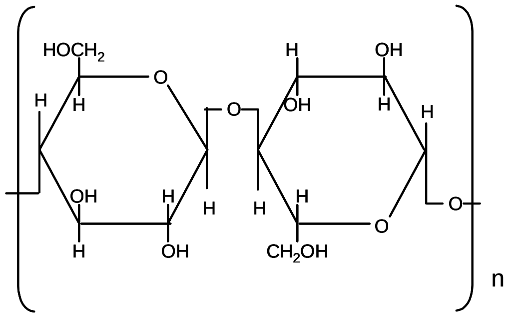
2.7 Cellulosic polymers

Cellulosic polymers (or: cellulosics) are produced by chemical modification of natural cellulose. The main representatives are cellophane, a type of regenerated cellulose used for films, cellulose acetate, an ester derivative (for moulding, extrusion and films); and regenerated cellulose for fibres (including viscose/rayon and Lyocell). Cotton fibers and wood are the primary raw materials for the production of industrially used cellulose (Krässig, 1997).

Cellulose is one of the main cell wall constituents of all major plants, both nonlignified (such as cotton) and lignified (such as wood) and constitutes as such the major portion of all chemical cell components. It is also found in the cell walls of green algae and the membranes of most fungi. So-called bacterial cellulose is synthesized by *Acetobacter xylinum* on nutrient media containing glucose (Krässig, 1997).

Cellulose (Figure 2-26) is a complex polysaccharide $(C_6H_{10}O_5)_n$ with crystalline morphology. Chemically, cellulose is similar to starch. It is a polymer of glucose in which the glucose units are linked by β-1,4-glucosidic bonds, whereas the bonds in starch are predominantly α-1,4-linkages (Callihan and Clemmer, 1979). Like starch, cellulose yields only glucose on complete hydrolysis by acid (Roberts and Etherington, 2003). Cellulose is more resistant to hydrolysis than starch, however. This resistance is due not only to the primary structure based on glucosidic bonds but also, to a great extent, to the secondary and tertiary configuration of the cellulose chain bonds (strong hydrogen bonds may form between neighbouring chains), as well as its close association with other protective polymeric structures such as lignin, starch, pectin, hemicellulose, proteins and mineral elements (Callihan and Clemmer, 1979). For this reason, cellulose modification is costly, requiring quite harsh processing conditions (Petersen et al., 1999).

Figure 2-26: The structure of cellulose



Cellulose was first used as a basis for polymer production in the mid- to late-19th century, when applications in both films and fibres were developed. One of the first cellulosic films was cellulose nitrate, which was introduced as a base material for photographic emulsions. Due to its flammability, it was later replaced by cellulose triacetate. Other important early cellulose-based films were derived from cellulose acetate and cellulose hydrate. Up until the 1950s, cellulose hydrate films (cellophanes) dominated the packaging field. In particular, cellophane coated with cellulose nitrate or poly(vinylidene chloride) found extensive applications due to its low permeability to water vapor and oxygen, coupled with desirable sealing properties (Stickelmeyer, 1969).

Following the introduction of polyolefin films in the 1950s with their easy processability, durability and good mechanical properties, films from cellulosic polymers lost their market dominance. Cellulosics, with their relatively high price compared to petrochemical polymer replacements, were relegated to comparatively low volume or niche applications. This is evidenced by statistics for the global production of man-made cellulosic fibres (IVC, 2003) from the period 1970 to 2000, showing the relative stagnation of cellulosic fibres compared to a tenfold increase in man-made synthetic fibres (Figure 2-27). The production of cellulosic fibres (IVC, 2003) compared to cellulosic plastics (UNICI, 2002) is shown in Figure 2-28; in general, the volume of cellulosic plastics has been about one tenth of that of cellulosic fibres; production of cellulosic plastics has thus also stagnated. Although there have been improvements recently in regenerated cellulose technology (e.g. lyocell, cellulose coating technologies), there it seems unlikely that cellulosics will attain sufficient competitiveness to grow their market share over other polymers and may even lose further ground to newly developing bio-based polymer alternatives. This section will thus provide only a brief summary of cellulosics technologies and the current market for these polymers.

Figure 2-27: Production of man-made versus cellulosic fibres since 1970

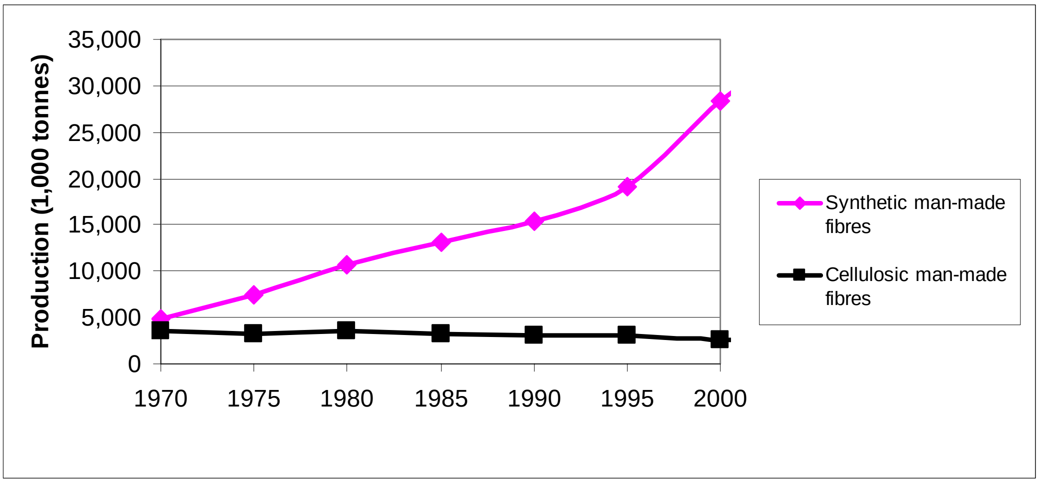
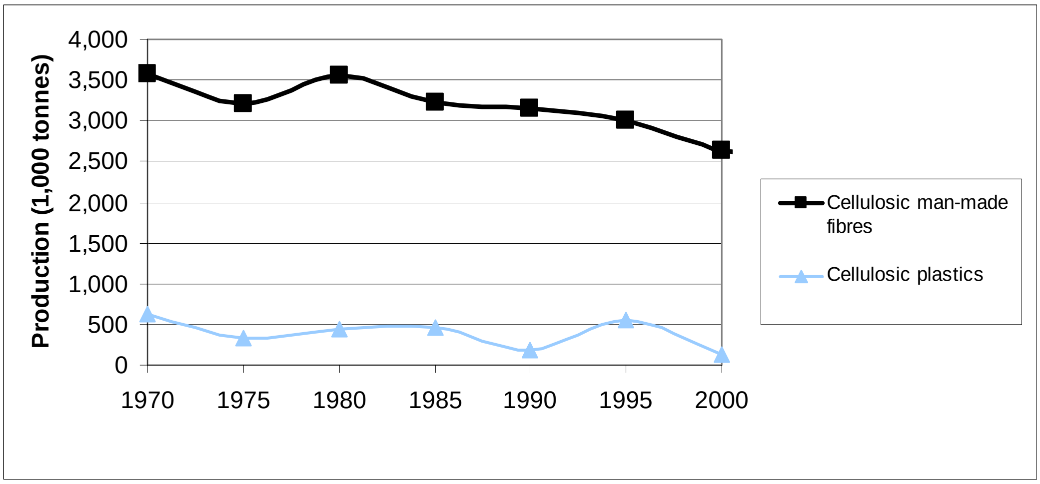


Figure 2-28: Production of cellulosic fibres and plastics[1] since 1970 (IVC, 2003) and (UNICI 2002)



[1] Cellulosic plastics is the category 'Regenerated cellulose' which is defined as the net dry content of regenerated cellulose, cellulose nitrate, cellulose acetate and other cellulose derivatives (UNICI 2002)

2.7.1 Production

Cellulosic polymers are produced primarily from wood but sometimes cellulose from short cotton fibres, called linters, is used. Linters contain up to 95% pure cellulose together with small amounts of proteins, waxes, pectins, and inorganic impurities. Wood pulps give a much lower yield of cellulose (Krässig, 1997). There are currently two processes used to separate cellulose from the other wood constituents. These methods, sulfite and prehydrolysis kraft pulping, use high pressure and chemicals to separate cellulose from lignin and hemicellulose, and to attain greater than 97% cellulose purity. The cellulose yield by these methods is 35-40% by weight (OIT, 2001). Cellophane, a type of regenerated cellulose, is made by grinding up cellulose from wood pulp and treating it with a stong alkali (caustic soda). After the ripening process during which depolymerisation occurs, carbon disulphide is added. This forms a yellow crumb known as cellulose xanthate [ROCSSH], which is easily dissolved in more caustic soda to give a viscous yellow solution known as ‘viscose’ (CIRFS, 2003). The viscose is then extruded into an acid bath for regeneration as a film.

Other main types of cellulose polymers are produced as follows (SPI, 2003):

- cellulose acetate [$CH_3COOC_2H_5$] is made by reacting **cellulose with acetic acid**
- cellulose acetate butyrate is a mixed ester produced by treating fibrous cellulose with butyric acid [$CH_3CH_2CH_2COOH$], butyric anhydride [$(CH_3CH_2CH_2CO)_2O$], acetic acid [CH_3COOH] and acetic anhydride [$(CH_3CO)_2O$] in the presence of sulfuric acid [H_2SO_4]; cellulose propionate is formed by treating fibrous cellulose with propionic acid [$CH_3CH_2CO_2H$] and acetic acid and anhydrides in the presence of sulfuric acid
- cellulose nitrate is made by treating fibrous cellulosic materials with a mixture of nitric [HNO_3] and sulfuric acids.

Because cellulose contains a large number of hydroxyl groups, it reacts with acids to form esters and with alcohols to form ethers. By such derivatisation reactions, hydrogen bonding is prevented. This provides an option for forming cellulose melts without the use of aggressive solvents. However, biodegradability decreases as the number of these derivatised OH groups increases (BenBrahim, 2002) so gains in terms of processability must be weighed up against loss of biodegradability, if desired.

Cellulosic Fibres

Viscose (rayon) fibres are made by the same process as that described previously for cellophane, except that the viscose (cellulose xanthate) solution is pumped through a spinneret, which may contain thousands of holes, into a dilute sulphuric acid bath so that the cellulose is regenerated as fine filaments as the xanthate decomposes (CIRFS, 2003).

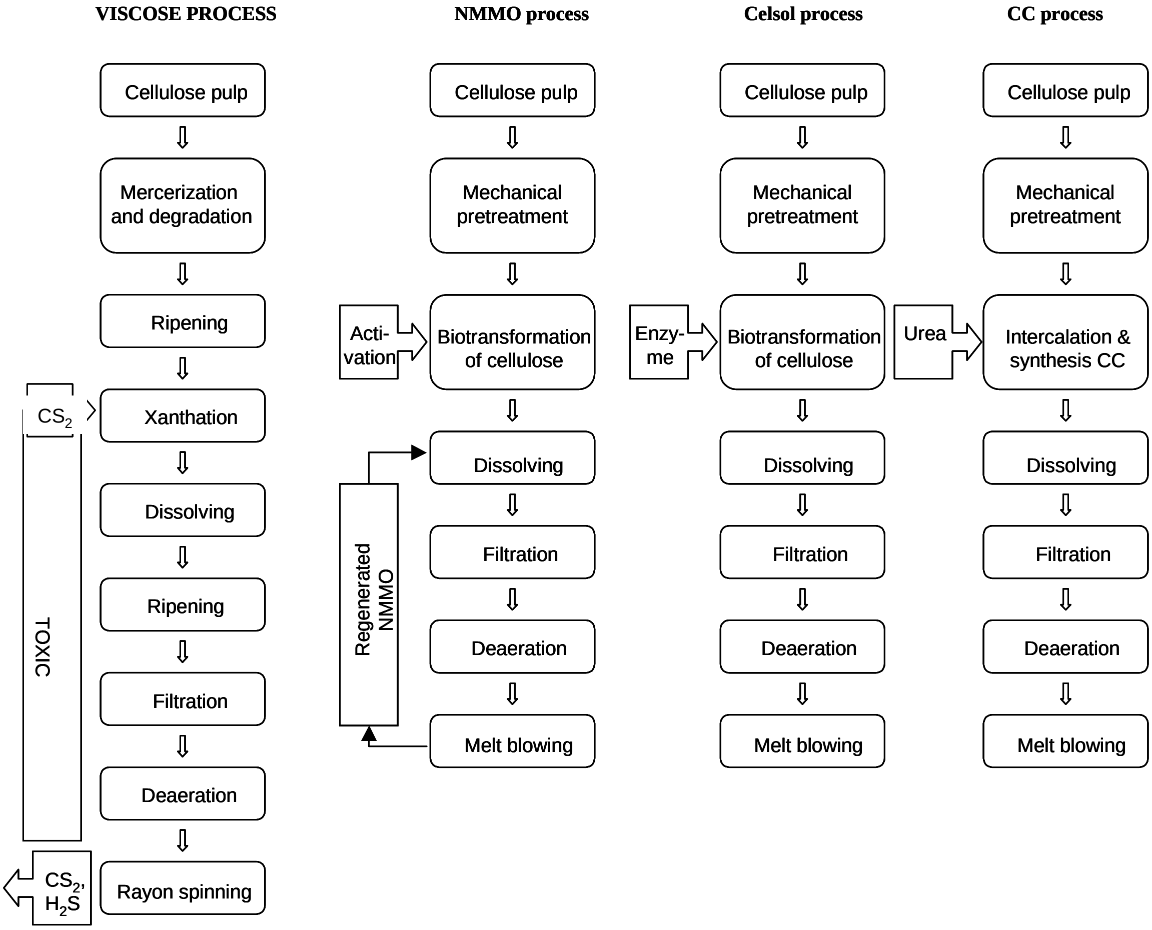
Other basic manufacturing techniques for the production of regenerated cellulose fibre include the cuprammonium process; the polynosic (modal) process, which is similar to the viscose process but with a higher degree of polymerisation and a modified precipitating bath (CIRFS, 2003); and the now obsolete nitrocellulose and saponified acetate processes (Thornton, 2002).

As recently as 1992 there has been a new process developed for producing regenerated cellulose fibers: the lyocell process (also called "solvent-spun"), developed by Courtaulds (Fibresource, 2003). In this process, cellulose pulp is dissolved in the solvent N-methylmorpholine n-oxide (NMMO) containing just the right amount of water. The solution is then filtered and passed through spinnerets to make the filaments, which are spun into water. The NMMO solvent is recovered from this aqueous solution and reused (CIRFS, 2003).While lyocell is sufficiently different from viscose rayon to almost be in a class by itself, it is classified as a subclass of rayon (regenerated cellulose) in the US (Thornton, 2002).

Struszczyk et al. (2002a) compare two new technologies for the production of cellulosic fibres, Celsol and Cellulose Carbamate (CC), with viscose and Lyocell (NMMO)

(Figure 2-29). The Lyocell process described here is reportedly not the same as Lenzing (Struszczyk, 2002b). The Celsol process is still under development. The Celsol and CC processes are similar to the Lyocell process except that NMMO as cellulose activating agent is replaced by enzyme in the Celsol process and urea in the CC process. According to the study, the Lyocell process uses the least amount of chemicals in comparison to the other processes (Struszczyk, 2002b).

Figure 2-29 Process for Viscose, Lyocell (NMMO), Cellulose carbamate (CC) and Celsol (Struszczyk et al., 2002a))



Cellulose acetate, being soluble in organic solvents such as acetone, is also suitable for spinning into fibre or forming into other shapes. The term acetate fibres is used to describe fibres made from cellulose acetate[18]. Wood cellulose is swollen by acetic acid, converted to cellulose acetate using acetic anhydride, and then dissolved in acetone. The resulting viscous solution is pumped through spinnerets into warm air to form filaments. The acetone evaporates and is recovered. The filaments are then wound up as filament yarns or collected as a tow (CIRFS, 2003).

Bacterial Cellulose

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[18] The difference between diacetate and triacetate fibres lies in the number of the cellulose hydroxyl groups that are acetylated. For acetate fibres the number lies between 75% and 92%, for triacetate fibres it is more than 92%. (CIRFS, 2003).

Although cellulose for industrial purposes is usually obtained from plant sources, considerable efforts are now being focused on cellulose production by an acetic acid-producing bacterium *Acetobacter xylinum* under conditions of agitated fermentation. A wide variety of substrates, including agricultural waste products, can be accepted by this bacterium and the process has good potential for large-scale production (Titech, 2001).

2.7.2 Properties

Cellulosics have good mechanical properties but are moisture sensitive. Cellophane film is generally coated with nitrocellulose wax (NCW) or polyvinylidene chloride (PVDC) to improve its moisture barrier properties. Cellophane has a good gas barrier at low relative humidity, but the barrier is reduced as humidity increases. As the theoretical melt temperature is above the degradation temperature, cellulose is not thermoplastic and therefore cannot be heat sealed (Weber et al., 2000). On the other hand, cellulose esters and cellulose ethers are thermoplastic. Cellulose derivatives including cellulose acetate contain up to 25% plasticiser to be suitable for thermoplastic processing. Many other cellulose derivatives posses excellent film-forming properties but are simply too expensive for bulk use. Cellulose acetate, cellulose butyrate and cellulose propionate, commonly used in electrical and electronics applications, have antistatic properties despite high electrical resistance, are crystal clear, tough, hard, scratch-resistant, insensitive to stress cracking, readily dyeable with brilliant colours, but are not permanently weather resistant (Kamm and Schüller, 1997).

Viscose (regenerated cellulose) fibre, like cotton, has a high moisture regain. It dyes easily, it does not shrink when heated, and it is biodegradable. Modal fibres and polynosic fibres are both high wet modulus fibres with improved properties such as better wear, higher dry and wet strengths and better dimensional stability (CIRFS, 2003). Acetate fibres are different from viscose in that they melt, are dyed using disperse dyes, absorb little water and can be textured. Although the dry strengths of the two types are similar, triacetate has a higher wet strength. It also has a high melting point (300 °C, compared with 250 °C for diacetate). Main end-uses for the filament yarns are linings and dresswear. There is very little staple fibre made from these fibres but acetate tow is the major product used for cigarette filters (CIRFS, 2003). Lyocell fibres are moisture absorbent, biodegradable and have a dry strength higher than other cellulosics and approaching that of polyester. They also retain 85% of their strength when wet. Lyocell fibres are mostly used for apparel fabrics (CIRFS, 2003).

Bacterial cellulose (‘biocellulose’) is chemically pure, free of lignin and hemicellulose, has high polymer crystallinity and a high degree of polymerization that distinguishes it from other forms of cellulose (Rensselaer, 1997). The diameter of bacterial cellulose is about 1/100 of that of plant cellulose and the Young's modulus is almost equivalent to that of aluminum. It can thus be used to produce molded materials of relatively high strength (Titech, 2001).

2.7.3 Technical substitution potential

In the fibre sector, regenerated cellulose and cellulose derivatives substitute for natural cellulose fibre and other natural and synthetic fibres. Cellulosics - in particular, acetate and xanthate esters for fibres - can technically partially replace polyester, nylon, and polypropylene, e.g. cellulose acetate blended with thermoplastic starch in place of a synthetic thermoplast. When compared to polyester, nylon, and polypropylene (fibres), cellulosics fair unfavourably, having a lower strength to weight ratio and less resistance to rot, mildew, burning, and wrinkling (Krässig, 1997). In the future, another possible substitution route will be bacterial cellulose substituting for standard cellulosics and for non-cellulosics in high-end applications.

2.7.4 Applications today and tomorrow

Apart from applications in the thin films sector, cellulosic polymers can also be used in moulding and extrusion processes (eFunda, 2003). Cellulose acetate, cellulose acetate butyrate and cellulose acetate propioniate are among the derivatives used to make a wide range of products including knobs, appliance housings, handles, toys, packaging, consumer products, and automotive parts (CTS, 2003), as well as electric insulation films, lights and casings (Kamm and Schüller, 1997).

Regenerated cellulose fibre (viscose) is used in most apparel end-uses, often blended with other fibres, and in hygienic disposables where its high absorbency gives advantages. In filament yarn form it is excellent for linings. It is used very little in home furnishing fabrics but in the industrial field, because of its thermal stability, a high modulus version is still the main product used in Europe to reinforce high speed tyres (CIRFS, 2003). Of the several different cellulose derivatives which have been investigated for fibres, only two, the acetate and xanthate esters, are of commercial importance for today (Fibresource, 2003).

Currently, applications for bacterial cellulose outside the food and biomedical fields are rather limited, and prices are still very high. One example is the acoustic diaphragms for audio speakers produced by Sony Corporation. Paper that is coated with bacterial cellulose is extremely smooth and protects the underlying fibres from moisture. Other possible bulk applications include use in oil and gas recovery, mining, paints and adhesives. Thus, although bacterial cellulose is a potentially important polymer, its interest in terms of bulk production of plastics is rather limited (OTA, 1993).

2.7.5 Current and emerging producers

As the cellulosic polymer industry as a whole is quite mature (apart from bacterial cellulose), the companies producing the established cellulose products are also those involved in innovations and technological progress in the field (see section 2.7.7). Producers of cellulosic thermoplasts (cellulose acetate, butyrate, propionate) include Courtaulds Plastic Group, UK (Dexel®); American polymers, USA (Ampol®); and Eastman Chemical International, USA (Tenite) (Kamm and Schüller, 1997), IFA, Mazzuchelli and UCB. Main producers of cellulosic fibres include Lenzing and Acordis (lyocell, viscose, modal), Glanzstoff (industrial viscose filament yarn) and SNIA (viscose, textile) (CIRFS, 2003). Bacterial cellulose is produced by Weyerhauser in the US (under the name Cellulon) and Ajinimoto in Japan (OTA, 1993).

2.7.6 Expected developments in cost structure and selling price

In view of the complex processing required, cellulose has a relatively high market price even today; in the range of € 3.00 - € 4.00 per kg which is substantially higher than that of polyolefins or other petrochemical-based polymers typically used as substitutes.

The study by Struszczyk et al. (2002) of four different cellulosic fibre processes found that the environmental protection costs[19] were highest for Viscose, then, in order of decreasing costs, Lyocell (figure not reported due to confidentiality), Cellulose carbamate (CC) (40% of Viscose) and Celsol (30% of Viscose). In terms of other production costs, Struszczyk reports that capital and personnel costs are slightly lower for CC and substantially less for Celsol compared to Viscose (Western Europe). The Celsol process also has a lower energy cost. Total operating costs (excluding environmental protection costs) are about 88% and 70% respectively for CC and Celsol compared to Viscose (figure for Lyocell not reported). These data indicate that substantial reductions in operating costs, waste products and energy usage may still be achieved in the production of cellulosic fibres – and by extension, cellulosic plastics. Nevertheless, this is unlikely that such process improvements will result in cellulosics becoming price competitive with petrochemical equivalents. Further technology advances with respect to separation of lignocellulosics or major developments in bacterial cellulose would be required to drive down the cost of cellulosics.

2.7.7 Environmental Impacts

Feedstocks

As mentioned in Section 2.7.1, the cellulose yield from wood is quite low. Additionally, the standard processes for cellulose production, involving washing and bleaching with chlorine, chlorine dioxide or hydrogen peroxide, result in malodorous emissions and deliver the cellulose and hemicellulose in an unusable form. In the U.S., the National Renewable Energy Lab, Eastman Chemical Company and a major producer of chemical-grade cellulose are investigating the scale-up and commercialisation of a more energy-efficient process to separate cellulose from lignin and hemicellulose in wood using a technology called Clean Fractionation (OIT, 2001). This separation technology has a higher cellulose yield of 47-48% by weight (compared to 35%-40% for standard processes) and allows for the use of the lignin and hemicellulose as feedstock for higher value chemicals as compared to the conventional technologies which use the lignin and hemicellulose as fuel. 99% of the organic solvent is recovered and reused, thereby eliminating the odorous emissions and minimizing the downstream effluent treatment. The resulting cellulose requires minimal further purification for use by the chemical industry compared with cellulose from the two conventional pulp and paper processes. Elimination of the high pressure conditions and use of chemicals will result in a significant processing energy reduction.

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[19] It is assumed that environmetal protection costs relate to the financial burden associated with cleaning or otherwise safely disposing of all waste streams.

Cellulosics production

As mentioned in Section 2.7.1, the production of cellulosics from cellulose pulp requires harsh chemical treatment; e.g. precipitation with carbon disulphide and dissolution with caustic soda. The process has relatively high energy and water requirements (UK Ecolabelling Board, 1997; see Table 2-31).

Table 2-31: Cradle-to-factory gate energy requirements for cellulosic and petrochemical polymers

Polymer	Energy*) GJ/t polymer	Reference
Cellulose polymers		
Regenerated cellulose (Lyocell)	77	Eibl et al., 1996
Regenerated cellulose (Rayon)	93	UK Ecolabelling Board, 1997
Cellulose hydrate films (cellophane)	92	Vink et al., 2003
Cellulose acetate	89	UK Ecolabelling Board, 1997
Petrochemical polymers		
Polyolefins*)	76	Boustead (1999/2000) *)
PET, amorphous	77	Boustead (2002)
PET, bottle grade	79	Boustead (2002)

*) Non-renewable energy only (finite energy); total of process energy and feedstock energy

**) 50% LLDPE + 50% HDPE)

The aforementioned study by Struszczyk et al. (2002) (sections 2.7.1, 2.7.6) indicates that sizeable improvements in the environmental impact (in terms of energy consumption and water use) of cellulosics are still possible should the described new processing technologies be adopted by industry.

2.8 Conclusions relating to existing and emerging technologies for bio-based polymers

This section attempts to draw together key points relating to the various groups of bio-based polymers already discussed in some detail, and to summarise the technology development phase, the substitution potential and the production cost in relation to each.

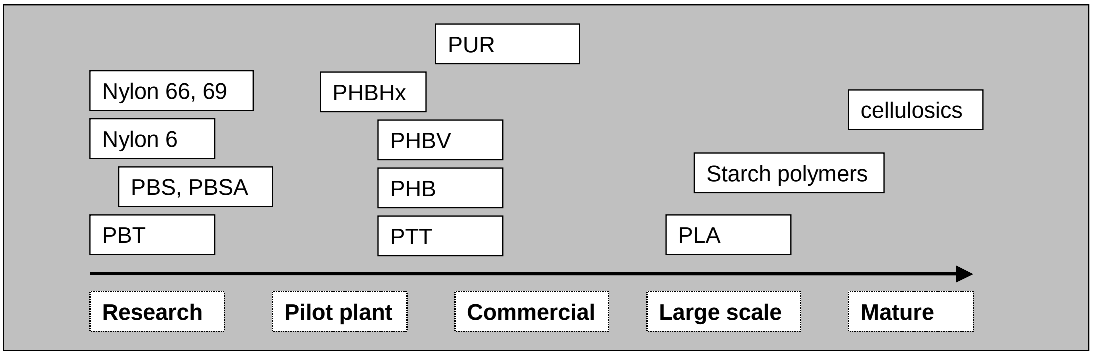
2.8.1 Technology development phase

Figure 2-30 illustrates the phase of development for the various bio-based polymers. Nylons with a bio-based component are in an early stage of development, development of PBT is awaiting advances in fermentation of 1,4-butanediol; while PBS is approaching pilot plant stage due to Japanese developments (Ajinimoto/Mitsubishi) in the area of large-scale succinic acid fermentation.

Between the pilot plant and commercial stage are the polyhydroxyalkanoates (PHBV, PHB, PHBHx), the main hurdles being relatively expensive, high quality fermentation substrates and relatively low conversion rates (20% wt/wt biomass for PHA). The aspirations of P&G and Metabolix to produce PHAs in bulk volumes are likely to advance the technology to the commercial stage by 2005, with large scale (30 to 50 kt) production at full capacity before 2010. Bio-based PTT should be produced commercially in 2006 if DuPont holds to its business plan. Progression to a large-scale process should be quite rapid once the fermentation of PDO is proven, since polymerisation plants for PTT are already in use. With PURs, high prices for polyols and costs associated with chemical manipulation of feedstocks to increase hydroxy functionality are the main barriers to entering bulk markets.

At the mature end of the scale, cellulosics are longest on the market and also have the least potential to achieve a breakthough either in cost or on the environmental front. For this reason, it is understood that in the coming years they will be overtaken in volume terms and substituted at least partially by other BBPs. As discussed extensively in Chapter 2.2, PLA is well on the road to penetrating bulk markets, with Cargill Dow's corn starch-based process presently ramping up to full production (140 kt) and Hycail launching efforts to commercialise PLA produced from whey. Starch polymers cover a somewhat wider range of product stages: while some products are rather mature and have been successful on the market for several years (e.g., loose fill packaging material), others have been produced on a large scale only recently (e.g. Goodyear's EcoTyre or Rodenburg's Solanyl).

Figure 2-30: Development stage of main bio-based polymer types



Abbrev.	Class Name
Nylon	Polyamide
PLA	Polylactic acid
PTT	Polytrimethyleneterephthalate
PBT	Polybutyleneterephthalate
PBS	Polybutylene succinate
PBSA	Polybutylene succinate adipate
PHB	Polyhydroxybutyrate (type of PHA)
PHBV	Polyhydroxybutyrate-co-hydroxyvalorate (type of PHA)
PHBHx	Polyhydroxybutyrate-co-hydroxyhexanoate (type of PHA)
PUR	Polyurethanes

2.8.2 Maximum technical substitution potential

To obtain a quantitative estimate of the substitution potential for bio-based polymers, estimates for the technical subsitution potential on a material-by-material basis have been compiled based on interviews with industry experts, thereby obtaining an overall estimate for the maximum possible substitution potential. This has been done both for plastics (Table 2-32) and fibres (Table 2-33). To the qualitative scale of increasing substitution potential (no potential, "-" to very high potential, "+++", see e.g. Table 2-9) shown in the legend of Table 2-32, a quantitative figure has been matched (0% to 30%). The figure 30% has been taken to indicate ample possibilities for direct substitution. The fact that the figure is not 100% is due to only partial replacement of petrochemical with renewable feedstocks, as well as only selected polymers within a type category (e.g. PTT in the category 'other polyesters', plant oil and polyester polyol PURs in category 'Bio-based PUR' and Nylon 6 and 6,6 in the category 'Bio-based PA').

In summing the figures in Table 2-32 (plastics) we see that, depending on the polymer, between 0% and 70% of the current volume could in theory be replaced by bio-based alternatives. Multiplying this by tonnes produced (lower table), volume estimates are obtained both by bio-based polymer category (rows), as well as by petrochemical-based polymer (columns). The overall maximum substitution potential for plastics is 14.7 million tonnes, corresponding to 34% (weighted) of the total current polymer production in EU-15. From Table 2-33 (fibres), the overall maximum substitution potential for fibres is estimated at 700 thousand tonnes, corresponding to 20% (weighted) of the total current fibre production in EU-15. For total polymers (plastics plus fibres), the **maximum substitution potential of bio-based polymers** in place of petrochemical-based polymers is thus estimated at **15.4 million tonnes, or 33% of total polymers**. As a note of caution, this figure should be viewed as indicative only, as it results from the combination of several uncertain estimates. In the very long term (2030 onwards), substitution could be even higher, depending upon the pace of development of a bio-based economy, but this is beyond the scope of the present study.

Table 2-32: Technical substitution potential of bio-based polymers (plastics) in Western Europe

% Substitution	PE-LD	PP	PVC	PE-HD	PS 1)	PET	PUR	PA	ABS 2)	PC	PMMA	POM 3)	other poly
Starch polymers	10	10	0	10	10	0	10	0	0	0	5	0	0
PLA	0	10	0	10	10	10	0	10	0	0	5	0	0
Other bio-based polyesters	0	20	0	0	0	30	0	30	0	20	5	0	0
PHA	20	20	10	30	20	10	10	0	10	0	5	0	0
Bio-based PUR	0	0	0	0	0	0	30	0	0	0	0	0	0
Bio-based PA	0	0	0	0	0	0	0	30	0	0	0	0	0
Sum percentages	30	60	10	50	40	50	50	70	10	20	20	0	0

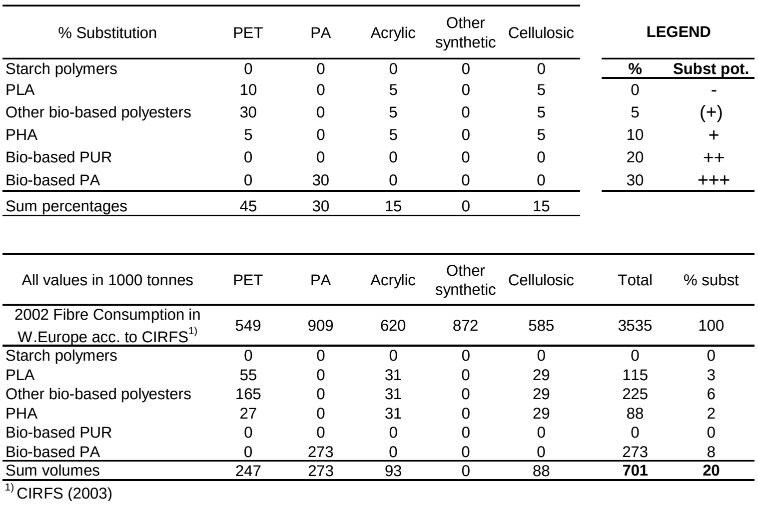
LEGEND

%	**Subst pot.**
0	-
5	(+)
10	+
20	++
30	+++

All values in 1000 tonnes	PE-LD	PP	PVC	PE-HD	PS 1)	PET	PUR	PA	ABS 2)	PC	PMMA	POM 3)	other poly	Total	% subst
1999 Polymer Consumption in W.Europe acc. to APME 4)	7,228	7,506	5,799	4,847	3,415	2,899	2,268	1,234	646	336	300	166	7,133	43,777	100
Starch polymers	723	751	0	485	342	0	227	0	0	0	15	0	0	2,541	6
PLA	0	751	0	485	342	290	0	123	0	0	15	0	0	2,005	5
Other bio-based polyesters	0	1,501	0	0	0	870	0	370	0	67	15	0	0	2,823	6
PHA	1,446	1,501	580	1,454	683	290	227	0	65	0	15	0	0	6,260	14
Bio-based PUR	0	0	0	0	0	0	680	0	0	0	0	0	0	680	2
Bio-based PA	0	0	0	0	0	0	0	370	0	0	0	0	0	370	1
Sum volumes	2,168	4,504	580	2,424	1,366	1,450	1,134	864	65	67	60	0	0	**14,681**	**34**

1) PS (all types) and EPS
2) ABS/SAN
3) Also known as polyacetal, polyformaldehyde
4) APME (2003)

Table 2-33: Technical substitution potential of bio-based polymers (fibres) in Western Europe.



% Substitution	PET	PA	Acrylic	Other synthetic	Cellulosic
Starch polymers	0	0	0	0	0
PLA	10	0	5	0	5
Other bio-based polyesters	30	0	5	0	5
PHA	5	0	5	0	5
Bio-based PUR	0	0	0	0	0
Bio-based PA	0	30	0	0	0
Sum percentages	45	30	15	0	15

LEGEND

%	**Subst pot.**
0	-
5	(+)
10	+
20	++
30	+++

All values in 1000 tonnes	PET	PA	Acrylic	Other synthetic	Cellulosic	Total	% subst
2002 Fibre Consumption in W.Europe acc. to CIRFS[1)]	549	909	620	872	585	3535	100
Starch polymers	0	0	0	0	0	0	0
PLA	55	0	31	0	29	115	3
Other bio-based polyesters	165	0	31	0	29	225	6
PHA	27	0	31	0	29	88	2
Bio-based PUR	0	0	0	0	0	0	0
Bio-based PA	0	273	0	0	0	273	8
Sum volumes	247	273	93	0	88	**701**	**20**

1) CIRFS (2003)

This is an opinion shared by many of the companies we interviewed. Nevertheless, if only customer perception determines this price premium one would expect the product to cater only to a specialist market. When it comes to bulk markets, other factors determining the competitive stance of bio-based polymers must be duly considered. Some of these which have already been mentioned from a company or technology-based perspective will be adressed more systematically in the following section.

The examples of commercialised and prototype products made from bio-based products listed in Table 2-34 give an indication of the wide range of possibilities and activities in this field. Some websites where products may be viewed are listed below.

Examples of innovative bio-based products may be viewed at:

http://www.ibaw.org/deu/seiten/markt_produkte.html
http://www.novamont.com >applications
http://www.nodax.com/ >potential applications
http://www.cargilldow.com/corporate/nw_pack_food.asp >applications

Table 2-34: Innovative product examples using bio-based polymers

Product	Bio-based polymer	Commercialized (C) or in development/ demonstration stage (D)	Companies active*)
Packaging			
Films and trays for biscuits, fruit, vegetables and meat	PLA, starch polymers	C	Treophan, Natura, IPER; Sainsburys, etc.
Yoghurt cup (Cristallina)	PLA	C	Cristallina / Cargill Dow
Nets for fruit	Starch polymers	C	Novamont; Tesco
Grocery bags	Starch polymers	C	Novamont; Natura; Albert Heijn; Swiss/German supermarkets
Rigid transparent packaging of batteries with removable printed film on back side	PLA	C	Panasonic
Trays and bowls for fast food (e.g. McDonald's salad shaker)	PLA	C	McDonalds
Envelope with transparent window, paper bag for bread with transparent window	PLA	C/D	Mitsui
Agriculture and horticulture			
Mulching films	Starch polymers, PLA	C	Novamont, Cargill Dow
Tomato clips			Natura
Short life consumer goods			
Hygiene products such as diapers**, cotton swabs**	Starch polymers	C/D	Lacea
Stationary and pre-paid cards	PLA	C/D	
Longlife consumer goods			
Apparel, e.g. T-shirts, socks	PLA	C	FILA / Cargill Dow, Kanebo Gosen
Blanket	PLA	C	Ingeo
Mattress	PUR	C	Metzeler
Casing of walkman	PLA	C	Sony
CD (compact disk)	PLA	C/D	Sanyo Marvic Media / Lacea
Computer keys	PLA	C	Fujistsu
Small component of laptop housing	PLA	C	Fujistsu / Lacea
Spare wheel cover	PLA (composite with kenaf fibres)	C	Toyota (model type "Raum")
Automobile interiors including head liners and upholstery and possibly for trimmings	PLA	D	Toyota

*) List is not exhaustive

3. Scenarios for future prices and markets of bio-based polymers

The term “Scenario” comes from the field of theatres and films and initially meant the script of a play. In scientific terms, “scenarios” represent a methodological approach to looking at a future situation which is full of uncertainties. The historical development of the scientific scenario methodology was described by Becker (1988).

But scenarios are not forecasts. Instead they are more like pictures or sketches of possible situations. Scenarios tell us consistent stories about the way the world or a system will evolve over a period of time or in what condition the system will be in at a certain point in time. These "narrative descriptions of hypothetical futures draw attention to causal processes and decision points" (Kahn and Wiener, 1967). The scenario approach is a method for describing the main influencing factors for a future development in a given context and for illustrating different possible development paths. These paths could define future frame conditions. In this way, it becomes possible to draw up suitable strategies for action starting from the current state of the system regarded for each development path. In this sense, scenarios are aids for long-term strategically oriented planning. Scenarios as a method of system research have been applied at the Fraunhofer ISI since the mid-seventies (Bossel and Denton, 1977; Jochem et al., 1976).

In Section 3, various scenarios will be prepared for the future use of bio-based polymers in 2005, 2010 and 2020.

3.1 Main influencing factors and their interrelation

To prepare the ground for the market projections this section identifies and discusses, the main influencing factors of the use of bio-based polymers must be identified and listed. In addition, the social, economic, ecological and technological boundary conditions need to be analysed and described. To this end, scientific literature and relevant studies (such as Kaup 2002; Käb 2003a) have been screened.

An overview of the identified main influencing factors and their interrelation is given in a mental model in Figure 3-1. For selected factors, characteristics of their impeding or stimulating impact are given in Table 3-1. It was emphasised by the experts in the project workshop that the differences and competition between petro-based and bio-based polymers will decrease in the future due to the fact that almost every large polymer producer has its own bio-based polymer development. The factors in Table 3-1 show only the spectrum of possible future developments and so give the frame conditions of (simplified but illustrative) scenarios.
Figure 3-1 provides an overview of the main influencing factors for the future development of bio-based polymers and the interrelation of some of these factors in the form of a mind map.

This mind map organises the main influencing factors along the value chain for the whole life cycle, i. e. the production, use and waste management of bio-based polymers. This value chain comprises the following stages (Figure 3-2):

- Agricultural crop production and harvest,
- Industrial production and processing of bio-based polymers. In general, (at least) three different stages can be distinguished: the primary processing stage in which the agricultural raw materials are converted into basic materials or building blocks of bio-based polymers (e. g. starch production from maize, wheat or potato as the basic material for starch polymers, or lactic acid production from biomass as building block for poly-lactid polymers). In the secondary processing stage, intermediates such as films, granules or fibres of bio-based polymers are produced. In the third processing stage, the final processing of these intermediates to end products (such as containers, textiles etc.) takes place. The distribution and marketing stage provides the link between the producers and the users of the bio-based polymers. The different stages outlined here can be found in one company, but can also be accomplished by networks of independent companies.
- Moreover, the structure of the industry involved should be kept in mind which is closely interrelated with the market sizes, market segments and types of products that are or can be commercialized successfully. In general, large, often multinational companies have the know-how and the financial and organisational resources to build large production plants, and to target large, often multinational markets. The production of bulk bio-based polymers would most likely require the involvement of such large companies. On the other hand, small-scale products with limited turnover, albeit commercially successful, are often not attractive enough for the product portfolio of a large company. Another company type is the small and medium sized enterprises (SMEs). They are often more flexible and innovative, and products which target niche markets may be attractive business opportunities for these companies. On the other hand, their resources are often limited regarding large scale production, and the penetration of large, international markets.
- Use phase by customers.
- Waste management. This stage comprises different waste management options, such as recycling, waste disposal in landfill sites, composting, biogas production, incineration.

The value chain was chosen for sorting the main influencing factors, because several influencing factors exert their effects mainly on one or only a few stages, while others (can) have impacts along the entire value chain (see also branch "frame conditions" in the mind map).

In addition, it should be kept in mind that there are feedback loops between different stages of the value chain, which are not reflected in the mind map.

Figure 3-1: Mindmap of influencing factors

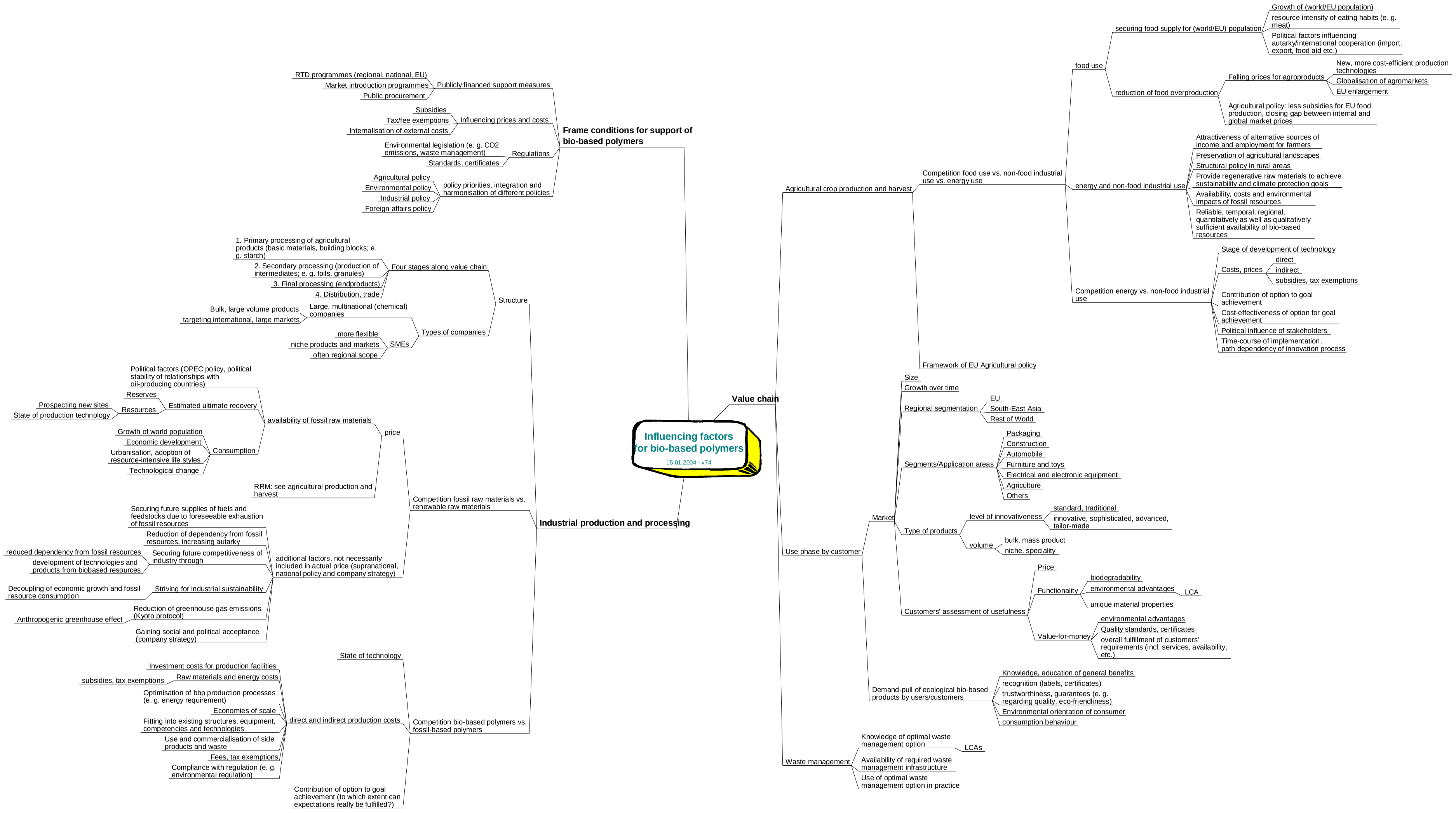


Figure 3-2: Value chain of bio-based polymers

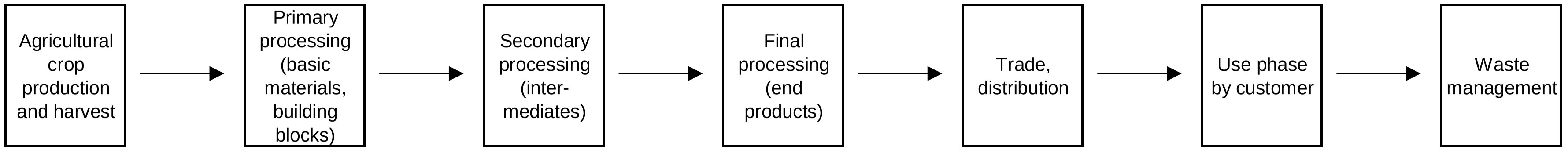


Table 3-1: Key influencing factors and characteristics of their impeding or stimulating impacts

Key influencing factors	**Characteristics for stimulating impacts of this factor**	**Characteristics for impeding impacts of this factor**
Frame conditions for support of bio-based polymers		
Policy priorities in agricultural policy	• Non-food industrial use of agricultural products is a political priority, because – of the need to reduce food overproduction by implementing set-aside programmes – non-food industrial use of agricultural products is assessed as useful contribution to attractive alternative source of income and employment for farmers, preservation of agricultural landscapes, structural policy in rural areas – integration and harmonisation of agricultural with environmental policy – of political influence of (agricultural) stakeholders	• Non-food industrial use of agricultural products is no political priority, because – of the need to secure the food supply for (world/EU) population – non-food industrial use of agricultural products is assessed as an inferior option to achieve income, employment, cultural landscape preservation, reduction of greenhouse gas emissions, in terms of availability, feasibility, impacts, cost-effectiveness, political support by stakeholders etc.

Key influencing factors	Characteristics for stimulating impacts of this factor	Characteristics for impeding impacts of this factor
Policy priorities in environmental policy	• Non-food industrial use of agricultural products is a political priority, because – this option contributes substantially to the achievement of greenhouse gas emission reduction goals – of the favourable eco-profile of bio-based polymer production and use over full life cycle	• Non-food industrial use of agricultural products is no political priority, because – measures to counteract the anthropogenic greenhouse effect are of low political priority – other measures/options are assessed as superior in terms of feasibility, cost-effectiveness, lack of adverse environmental impacts etc.
Policy priorities in industrial policy	• Non-food industrial use of agricultural products is a political priority, because – the need is assessed as urgent to secure future supplies of fuels and feedstocks due to foreseeable exhaustion of fossil resources – the need is assessed as urgent to decrease industrial independence of fossil resources – this option is assessed as a substantial contribution to securing future competitiveness of industry – this option is assessed as suitable to contribute to industrial sustainability – this option is assessed as suitable for certain industries to gain political and social acceptance	• Non-food industrial use of agricultural products is no political priority because – short-term goals are favoured over long-term strategies – other options are assessed as superior regarding feasibility, cost-effectiveness, return of investment, demand and market impacts etc. – other means to decouple economic growth and fossil resource consumption are favoured – goals other than industrial sustainability are favoured

Key influencing factors	**Characteristics for stimulating impacts of this factor**	**Characteristics for impeding impacts of this factor**
Policy priorities in foreign affairs policy	• Non-food industrial use of agricultural products is a political priority, because – enlargement of the EU leads to requirement for set-aside programmes in agricultural policy – political instabilities in/unreliable relationships with fossil resource exporting countries favour striving for autarky from fossil resources – WTO regulations favour domestic production of non-food agricultural products	• Non-food industrial use of agricultural products is no political priority, because – long-term supply of fossil resources from exporting countries is stable and reliable – WTO regulations favour a) agriculture for food use or b) agricultural production outside the EU – the EU has to strive for more autarky regarding food supply (less food imports) – the EU increases its food exports
Integration and harmonisation of different policies	• Synergies between different policies are achieved through integration and harmonisation; support measures are consistent, comprehensive and harmonised	• Different policies pursue inconsistent, contradictory goals regarding the non-food industrial use of agricultural products; support measures are patchy and not harmonised

Key influencing factors	Characteristics for stimulating impacts of this factor	Characteristics for impeding impacts of this factor
Regulations	• Regulations are in force which – compensate unjustified disadvantages of bio-based processes and products compared to fossil-based processes and products (e. g. tax exemptions as compensation for higher prices; internalisation of external costs) – make proven advantages of bio-based processes and products a requirement for industry and consumers (e. g. biodegradability, CO_2 -neutrality) – guarantee certain qualities of bio-based products and processes (e. g. through certificates, standards) – reduce the level of uncertainty for different stakeholders – are consistent, comprehensive and harmonised over the entire value chain	• Regulations are in force which – favour food or energy use of agricultural products over non-food industrial use, favour fossil-based products and processes over bio-based products and processes in an unjustified way – are inconsistent, patchy and only directed to individual aspects or single stages of the value chain
Publicly financed support schemes	• Publicly financed support schemes are implemented on a substantial scale • The implemented support schemes have long-term perspectives, comprise different, complementary measures which cover the whole value chain and have complementary goals (e. g. support of RTD, market introduction, public procurement, subsidies and tax or fee exemptions, standards and certificates, evaluations)	• Publicly financed support schemes are scarcely funded • The implemented support schemes are patchy or redundant, with short term perspectives, are ill-integrated so that synergies cannot be exploited

Key influencing factors	Characteristics for stimulating impacts of this factor	Characteristics for impeding impacts of this factor
Stages of the value chain		
Agricultural production and harvest	• A substantial share of the agricultural production is used for non-food industrial purposes, because – of corresponding policy priorities – influencial stakeholders support this option – it is competitive with (or even superior to) food and energy uses of agricultural production regarding technological development, costs, income for farmers, cost-effectiveness for achieving policy goals – it is competitive with fossil-based resources regarding reliability, temporal, regional, quantitatively and qualitatively sufficient availability – it is competitive with or even superior to fossil-based resources regarding costs, reliable availability and environmental impacts	• Only a minor share of the agricultural production is used for non-food industrial purposes, because – the relevant frame conditions strongly favour food production over non-food uses – the relevant frame conditions strongly favour energy uses over non-food industrial uses – this option cannot achieve the expected policy goals or to a lesser or less cost-effective level than competing options – large scale production is incompatible with important policy goals due to unintended, adverse effects (e. g. on the environment, structure of rural landscapes)

Key influencing factors	Characteristics for stimulating impacts of this factor	Characteristics for impeding impacts of this factor
Industrial production and processing – Competition between fossil raw materials and bio-based raw materials	• A substantial share of the polymer production uses bio-based raw materials, because – bio-based materials can compete on a cost basis (many preconditions), and – bio-based materials are reliably available in sufficient quality and quantity, and/or – additional, strategic reasons favour their use, such as securing future supplies of fuels and feedstocks independent of fossil resources, securing future competitiveness of industry, striving for industrial sustainability, gaining social and political acceptance, complying with regulation (e. g. Kyoto protocol), occupying a unique market niche	• Only a minor share of the polymer production uses bio-based raw materials, because – bio-based materials are inferior to fossil raw materials regarding costs, reliable availability, quantity and quality and therefore are only suitable for niche products, but are unattractive for large scale products – only SMEs, albeit innovative and flexible, but with limited resources regarding know-how, market penetration capability and mainly regionally restricted scope, find attractive market niches

Key influencing factors	Characteristics for stimulating impacts of this factor	Characteristics for impeding impacts of this factor
– Competition between fossil-based polymers and bio-based polymers (production)	• A substantial share of the polymer production is substituted by bio-based polymers, because – their production technology has reached an advanced, competitive stage, – both polymer types are competitive regarding their direct and indirect production costs, due to substantial improvements in e. g. process optimisation, exploiting economies of scale, use and commercialisation of by-products and waste etc. for bio-based polymers – disadvantages of bio-based polymers regarding their direct production costs are more than compensated by other advantages, such as superior functionality, subsidies and fee/tax exemptions for raw materials and products, compliance with pro-bio-based-polymer-regulations – not only bio-based products for the "environment market niche", but also bulk products for other market segments are commercially attractive	• The production of bio-based polymers remains restricted to certain market niches, because – competitiveness of the production processes on a cost-basis cannot be achieved for various reasons, and – biodegradability and production from bio-based materials remain the only unique features of bio-based polymers, so that the market segments remain restricted, – the production processes for bio-based polymers remain inferior to fossil-based polymer production regarding environmental impacts (e. g. energy use, green house gas emissions) or other goals (e. g. company profits, return of investment)

Key influencing factors	**Characteristics for stimulating impacts of this factor**	**Characteristics for impeding impacts of this factor**
Use phase by customer – Competition between fossil-based polymers and bio-based polymers (use)	• Customers prefer bio-based polymers over fossil-based polymers in sizeable market segments with above average growth rates, because – bio-based polymers are used both for the production of standard, traditional products as well as for innovative, sophisticated and tailor-made products, and are commercially successful for bulk products as well as niche products, – commercially viable applications can be found in all market segments, ranging from packaging, construction, automobile, furniture, electrical and electronic equipment to agriculture, medicine etc. – the bio-based products are superior to competing fossil-based products regarding either price, functionality or value-for-money – there is a strong demand-pull for ecological, bio-based products by the users – consumers are in the position to make their deliberate choices between between bio-based and fossil-based polymers (due to several factors)	• The use of bio-based polymers remains limited, because – their eco-image or their biodegradability are their only unique features, and the willingness to pay and the unique applications of such polymers are limited. – customers have no knowledge of the general advantages of bio-based polymers, cannot distinguish bio-based from fossil-based polymers, do not trust the said advantages of bio-based polymers (e. g. ecofriendliness, biodegradability) because of bad experiences or lack of guarantees, certificates etc, generally rank environmental issues low on their list of personal priorities, do not transform general awareness of environmental issues into behaviour

Key influencing factors	Characteristics for stimulating impacts of this factor	Characteristics for impeding impacts of this factor
Waste management	• The possible advantages of bio-based polymers regarding waste management are fully exploited, because – results from LCA studies are used to optimise bio-based polymers waste management, – the required optimised waste management infrastructure is implemented, – the optimised waste management options are used in practice	• Bio-based polymers perform poorly regarding waste management, because – of a lack of knowledge of optimised waste management options, – the existing waste management infrastructure differs a lot from an optimised waste management for bio-based polymers, and is unlikely to change due to several factors, – bio-based polymers are not channeled into the optimal waste management option, although this option is available

3.1.2 Scenarios for bio-based polymers in Europe

The combination of the development variants for all scenarios is shown using the columns and lines marked in the following consisitency matrices, see Figures 3-3 to 3-5. The scenarios selected only take one level of indirect influences into account; other levels can be calculated with computer simulations, but usually yield similar results. When interpreting the results, it should be kept in mind that the fields shown in grey should contain as few contradictions as possible (marked with a minus sign). However, this cannot be avoided completely in every scenario. A positive influence in the fields marked supports the trend of this combination of influencing factors and should occur as often as possible. Alternatives can be analysed by looking at how many contradictions or supporting influences result when selecting an alternative to the marked line and column. The descriptions of the selected development variants can be summarised in one description of the frame assumptions for the individual scenarios.

Among the different possibilities of scenarios we chose the three ones called **WITHOUT P&M, WITH P&M** and **HIGH GROWTH**.

In the scenario **WITHOUT P&M,** a business-as-usual picture is described: bio-based polymers are present in small and niche markets but are not able to compete with mass polymers such as PE or PVC. The oil and the crop prices are medium, economic growth is also average. There is no special support from either agricultural or environmental policy. Big new polymer plants with more than 400,000 kt.p.a. in one line are located outside Europe and keep the price for petrochemical polymers low.

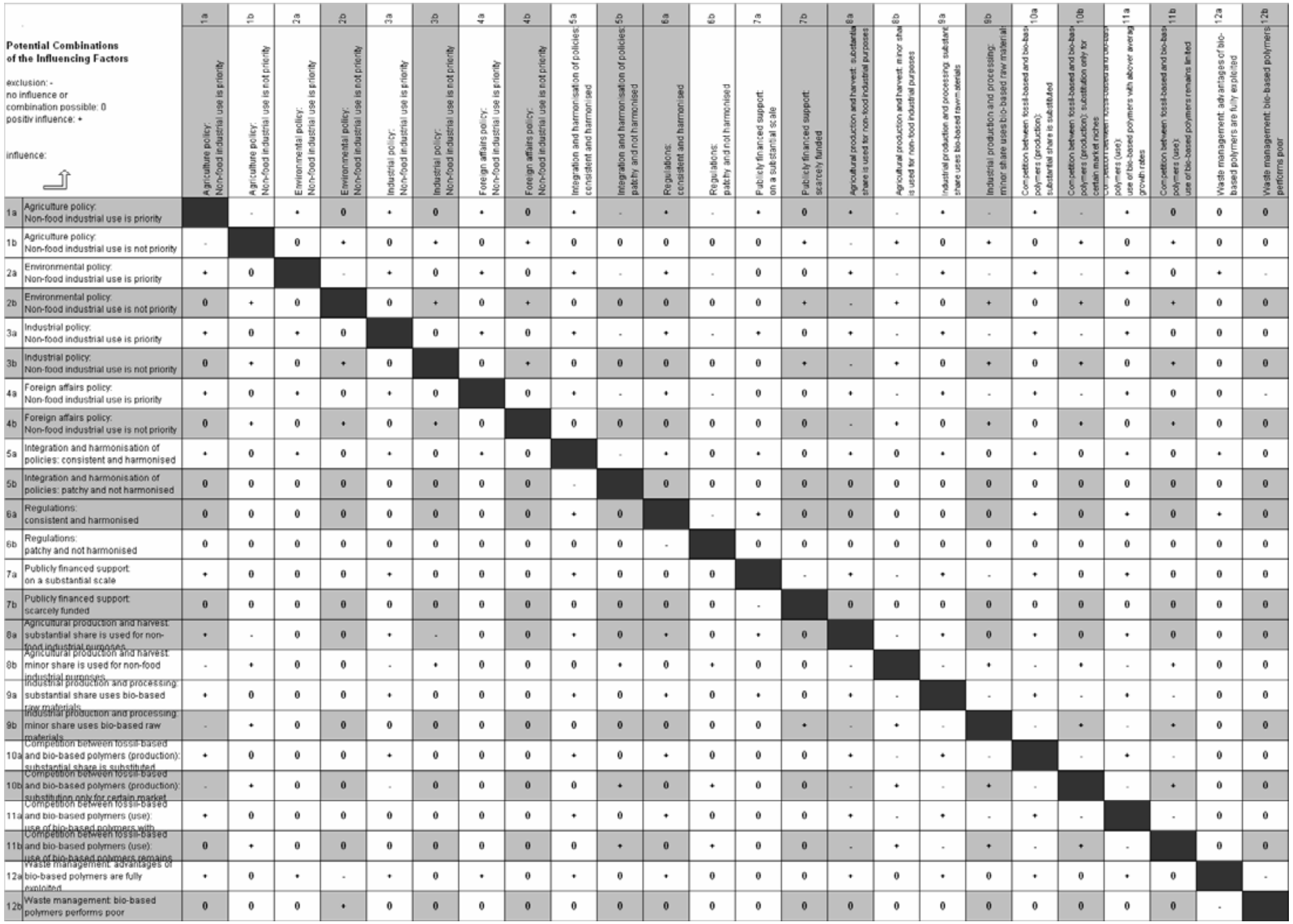
The **WITH P&M** scenario is situated between the WITHOUT P&M and the HIGH GROWTH scenario. There is some policy intervention supporting bio-based materials but this support is restricted because the advantages of these materials are not clear in all policy fields. For example, there may be support from agricultural policy makers because of the employment prospects, but not from the environmental side. GDP growth is high in this scenario, but energy prices are low as are crop prices.

In the **HIGH GROWTH** scenario, the production of bio-based polymers is supported by all sides: for environmental reasons, such as CO_2 abatement and for reasons of better land utility use for non-food crops, the policy makers in environmental and agricultural departments push the production of bio-based polymers. The frame conditions are characterised by medium crop prices and high oil prices. The consumers have been successfully informed to see the advantages of bio-based polymers so that a constant demand for them results. The capacities for petrochemical polymers outside Europe are required to meet the demand abroad and do not affect the market price in Europe. The demand overseas is so large that the market price for bio-based polymers is not forced downwards.

Figure 3-3: Consistency matrix for the WITHOUT P&M scenario

Potential Combinations of the Influencing Factors exclusion: - no influence or combination possible: 0 positiv influence: + influence: ↑		1a Agriculture policy: Non-food industrial use is priority	1b Agriculture policy: Non-food industrial use is not priority	2a Environmental policy: Non-food industrial use is priority	2b Environmental policy: Non-food industrial use is not priority	3a Industrial policy: Non-food industrial use is priority	3b Industrial policy: Non-food industrial use is not priority	4a Foreign affairs policy: Non-food industrial use is priority	4b Foreign affairs policy: Non-food industrial use is not priority	5a Integration and harmonisation of policies: consistent and harmonised	5b Integration and harmonisation of policies: patchy and not harmonised	6a Regulations: consistent and harmonised	6b Regulations: patchy and not harmonised	7a Publicly financed support: on a substantial scale	7b Publicly financed support: scarcely funded	8a Agricultural production and harvest: substantia share is used for non-food industrial purposes	8b Agricultural production and harvest: minor sha is used for non-food industrial purposes	9a Industrial production and processing: substant share uses bio-based raw materials	9b Industrial production and processing: minor share uses bio-based raw material	10a Competition between fossil-based and bio-bas polymers (production): substantial share is substituted	10b Competition between fossil-based and bio-bas polymers (production): substitution only for certain market niches	11a Competition between fossil-based and bio-bas polymers (use): use of bio-based polymers with abover averag growth rates	11b Competition between fossil-based and bio-bas polymers (use): use of bio-based polymers remains limited	12a Waste management: advantages of bio-based polymers are fully exploited	12b Waste management: bio-based polymers performs poor
1a	Agriculture policy: Non-food industrial use is priority		-	+	0	+	0	+	0	+	-	+	-	+	0	+	-	+	-	+	-	+	0	0	0
1b	Agriculture policy: Non-food industrial use is not priority	-		0	+	0	+	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
2a	Environmental policy: Non-food industrial use is priority	+	0		-	+	0	+	0	+	-	+	-	0	0	+	-	+	-	+	-	+	0	+	-
2b	Environmental policy: Non-food industrial use is not priority	0	+	0		0	+	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
3a	Industrial policy: Non-food industrial use is priority	+	0	+	0		0	+	0	+	-	+	-	+	0	+	-	+	-	+	-	+	0	0	0
3b	Industrial policy: Non-food industrial use is not priority	0	+	0	+	0		0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
4a	Foreign affairs policy: Non-food industrial use is priority	+	0	+	0	+	0		0	+	-	+	-	0	0	+	-	+	-	+	-	+	0	0	-
4b	Foreign affairs policy: Non-food industrial use is not priority	0	+	0	+	0	+	0		0	0	0	0	0	0	-	+	0	+	0	+	0	+	0	0
5a	Integration and harmonisation of policies: consistent and harmonised	+	0	+	0	+	0	+	0		-	+	0	+	0	+	0	+	0	+	0	+	0	+	0
5b	Integration and harmonisation of policies: patchy and not harmonised	0	0	0	0	0	0	0	0	-		0	0	0	0	0	0	0	0	0	0	0	0	0	0
6a	Regulations: consistent and harmonised	0	0	0	0	0	0	0	0	+	0		-	+	0	0	0	0	0	+	0	+	0	+	0
6b	Regulations: patchy and not harmonised	0	0	0	0	0	0	0	0	0	0	-		0	0	0	0	0	0	0	0	0	0	0	0
7a	Publicly financed support: on a substantial scale	+	0	0	0	+	0	0	0	+	0	0	0		-	+	-	+	-	+	0	+	0	0	0
7b	Publicly financed support: scarcely funded	0	0	0	0	0	0	0	0	0	0	0	0	-		0	0	0	0	0	0	0	0	0	0
8a	Agricultural production and harvest: substantial share is used for non-food industrial purposes	+	-	0	0	+	-	0	0	+	0	+	0	+	0		-	+	0	+	0	+	0	0	0
8b	Agricultural production and harvest: minor share is used for non-food industrial purposes	-	+	0	0	-	+	0	0	0	+	0	+	0	0	-		-	+	-	+	-	+	0	0
9a	Industrial production and processing: substantial share uses bio-based raw materials	+	0	0	0	+	0	0	0	+	0	+	0	+	0	+	-		-	+	-	+	-	0	0
9b	Industrial production and processing: minor share uses bio-based raw materials	-	+	0	0	0	0	0	0	0	0	0	0	0	+	-	+	-		-	+	-	+	0	0
10a	Competition between fossil-based and bio-based polymers (production): substantial share is substituted	+	0	0	0	+	0	0	0	+	0	+	0	0	0	+	-	+	-		-	+	-	0	0
10b	Competition between fossil-based and bio-based polymers (production): substitution only for certain market	-	+	0	0	-	0	0	0	0	+	0	+	0	0	-	+	-	+	-		-	+	0	0
11a	Competition between fossil-based and bio-based polymers (use): use of bio-based polymers with	+	0	0	0	0	0	0	0	+	0	+	0	0	0	+	-	+	-	+	-		-	0	0
11b	Competition between fossil-based and bio-based polymers (use): use of bio-based polymers remains	0	+	0	0	0	0	0	0	0	+	0	+	0	0	-	+	-	+	-	+	-		0	0
12a	Waste management: advantages of bio-based polymers are fully exploited	+	0	+	-	+	0	+	0	+	0	+	0	0	0	+	0	+	0	+	0	+	0		-
12b	Waste management: bio-based polymers performs poor	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	

Figure 3-4: Consistency matrix for the WITH P&M scenario



	Potential Combinations of the Influencing Factors exclusion: - no influence or combination possible: 0 positiv influence: + influence: ⮥	1a Agriculture policy: Non-food industrial use is priority	1b Agriculture policy: Non-food industrial use is not priority	2a Environmental policy: Non-food industrial use is priority	2b Environmental policy: Non-food industrial use is not priority	3a Industrial policy: Non-food industrial use is priority	3b Industrial policy: Non-food industrial use is not priority	4a Foreign affairs policy: Non-food industrial use is priority	4b Foreign affairs policy: Non-food industrial use is not priority	5a Integration and harmonisation of policies: consistent and harmonised	5b Integration and harmonisation of policies: patchy and not harmonised	6a Regulations: consistent and harmonised	6b Regulations: patchy and not harmonised	7a Publicly financed support: on a substantial scale	7b Publicly financed support: scarcely funded	8a Agricultural production and harvest: substantia share is used for non-food industrial purposes	8b Agricultural production and harvest: minor sha is used for non-food industrial purposes	9a Industrial production and processing: substant share uses bio-based raw materials	9b Industrial production and processing: minor share uses bio-based raw material	10a Competition between fossil-based and bio-bas polymers (production): substantial share is substituted	10b Competition between fossil-based and bio-bas polymers (production): substitution only for certain market niches	11a Competition between fossil-based and bio-bas polymers (use): use of bio-based polymers with above averag growth rates	11b Competition between fossil-based and bio-bas polymers (use): use of bio-based polymers remains limited	12a Waste management: advantages of bio-based polymers are fully exploited	12b Waste management: bio-based polymers performs poor
1a	Agriculture policy: Non-food industrial use is priority		-	+	0	+	0	+	0	+	-	+	-	+	0	+	-	+	-	+	-	+	0	0	0
1b	Agriculture policy: Non-food industrial use is not priority	-		0	+	0	+	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
2a	Environmental policy: Non-food industrial use is priority	+	0		-	+	0	+	0	+	-	+	-	0	0	+	-	+	-	+	-	+	0	+	-
2b	Environmental policy: Non-food industrial use is not priority	0	+	0		0	+	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
3a	Industrial policy: Non-food industrial use is priority	+	0	+	0		0	+	0	+	-	+	-	+	0	+	-	+	-	+	-	+	0	0	0
3b	Industrial policy: Non-food industrial use is not priority	0	+	0	+	0		0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
4a	Foreign affairs policy: Non-food industrial use is priority	+	0	+	0	+	0		0	+	-	+	-	0	0	+	-	+	-	+	-	+	0	0	-
4b	Foreign affairs policy: Non-food industrial use is not priority	0	+	0	+	0	+	0		0	0	0	0	0	0	-	+	0	+	0	+	0	+	0	0
5a	Integration and harmonisation of policies: consistent and harmonised	+	0	+	0	+	0	+	0		-	+	0	+	0	+	0	+	0	+	0	+	0	+	0
5b	Integration and harmonisation of policies: patchy and not harmonised	0	0	0	0	0	0	0	0	-		0	0	0	0	0	0	0	0	0	0	0	0	0	0
6a	Regulations: consistent and harmonised	0	0	0	0	0	0	0	0	+	0		-	+	0	0	0	0	0	+	0	+	0	+	0
6b	Regulations: patchy and not harmonised	0	0	0	0	0	0	0	0	0	0	-		0	0	0	0	0	0	0	0	0	0	0	0
7a	Publicly financed support: on a substantial scale	+	0	0	0	+	0	0	0	+	0	0	0		-	+	-	+	-	+	0	+	0	0	0
7b	Publicly financed support: scarcely funded	0	0	0	0	0	0	0	0	0	0	0	0	-		0	0	0	0	0	0	0	0	0	0
8a	Agricultural production and harvest: substantial share is used for non-food industrial purposes	+	-	0	0	+	-	0	0	+	0	+	0	+	0		-	+	0	+	0	+	0	0	0
8b	Agricultural production and harvest: minor share is used for non-food industrial purposes	-	+	0	0	-	+	0	0	0	+	0	+	0	0	-		-	+	-	+	-	+	0	0
9a	Industrial production and processing: substantial share uses bio-based raw materials	+	0	0	0	+	0	0	0	+	0	+	0	+	0	+	-		-	+	-	+	-	0	0
9b	Industrial production and processing: minor share uses bio-based raw materials	-	+	0	0	0	0	0	0	0	0	0	0	0	+	-	+	-		-	+	-	+	0	0
10a	Competition between fossil-based and bio-based polymers (production): substantial share is substituted	+	0	0	0	+	0	0	0	+	0	+	0	0	0	+	-	+	-		-	+	-	0	0
10b	Competition between fossil-based and bio-based polymers (production): substitution only for certain market	-	+	0	0	-	0	0	0	0	+	0	+	0	0	-	+	-	+	-		-	+	0	0
11a	Competition between fossil-based and bio-based polymers (use): use of bio-based polymers with	+	0	0	0	0	0	0	0	+	0	+	0	0	0	+	-	+	-	+	-		-	0	0
11b	Competition between fossil-based and bio-based polymers (use): use of bio-based polymers remains	0	+	0	0	0	0	0	0	0	+	0	+	0	0	-	+	-	+	-	+	-		0	0
12a	Waste management: advantages of bio-based polymers are fully exploited	+	0	+	-	+	0	+	0	+	0	+	0	0	0	+	0	+	0	+	0	+	0		-
12b	Waste management: bio-based polymers performs poor	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	

Figure 3-5: Consistency matrix for the HIGH GROWTH scenario

Potential Combinations of the Influencing Factors exclusion: - no influence or combination possible: 0 positiv influence: + influence:		1a Agriculture policy: Non-food industrial use is priority	1b Agriculture policy: Non-food industrial use is not priority	2a Environmental policy: Non-food industrial use is priority	2b Environmental policy: Non-food industrial use is not priority	3a Industrial policy: Non-food industrial use is priority	3b Industrial policy: Non-food industrial use is not priority	4a Foreign affairs policy: Non-food industrial use is priority	4b Foreign affairs policy: Non-food industrial use is not priority	5a Integration and harmonisation of policies: consistent and harmonised	5b Integration and harmonisation of policies: patchy and not harmonised	6a Regulations: consistent and harmonised	6b Regulations: patchy and not harmonised	7a Publicly financed support: on a substantial scale	7b Publicly financed support: scarcely funded	8a Agricultural production and harvest: substantia share is used for non-food industrial purposes	8b Agricultural production and harvest: minor sha is used for non-food industrial purposes	9a Industrial production and processing: substant share uses bio-based raw materials	9b Industrial production and processing: minor share uses bio-based raw materials	10a Competition between fossil-based and bio-bas polymers (production): substantial share is substituted	10b Competition between fossil-based and bio-bas polymers (production): substitution only for certain market niches	11a Competition between fossil-based and bio-bas polymers (use): use of bio-based polymers with above averag growth rates	11b Competition between fossil-based and bio-bas polymers (use): use of bio-based polymers remains limited	12a Waste management: advantages of bio-based polymers are fully exploited	12b Waste management: bio-based polymers performs poor
1a	Agriculture policy: Non-food industrial use is priority	■	-	+	0	+	0	+	0	+	-	+	-	+	0	+	-	+	-	+	-	+	0	0	0
1b	Agriculture policy: Non-food industrial use is not priority	-	■	0	+	0	+	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
2a	Environmental policy: Non-food industrial use is priority	+	0	■	-	+	0	+	0	+	-	+	-	0	0	+	-	+	-	+	-	+	0	+	-
2b	Environmental policy: Non-food industrial use is not priority	0	+	0	■	0	+	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
3a	Industrial policy: Non-food industrial use is priority	+	0	+	0	■	0	+	0	+	-	+	-	+	0	+	-	+	-	+	-	+	0	0	0
3b	Industrial policy: Non-food industrial use is not priority	0	+	0	+	0	■	0	+	0	0	0	0	0	+	-	+	0	+	0	+	0	+	0	0
4a	Foreign affairs policy: Non-food industrial use is priority	+	0	+	0	+	0	■	0	+	-	+	-	0	0	+	-	+	-	+	-	+	0	0	-
4b	Foreign affairs policy: Non-food industrial use is not priority	0	+	0	+	0	+	0	■	0	0	0	0	0	0	-	+	0	+	0	+	0	+	0	0
5a	Integration and harmonisation of policies: consistent and harmonised	+	0	+	0	+	0	+	0	■	-	+	0	+	0	+	0	+	0	+	0	+	0	+	0
5b	Integration and harmonisation of policies: patchy and not harmonised	0	0	0	0	0	0	0	0	-	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6a	Regulations: consistent and harmonised	0	0	0	0	0	0	0	0	+	0	■	-	+	0	0	0	0	0	+	0	+	0	+	0
6b	Regulations: patchy and not harmonised	0	0	0	0	0	0	0	0	0	0	-	■	0	0	0	0	0	0	0	0	0	0	0	0
7a	Publicly financed support: on a substantial scale	+	0	0	0	+	0	0	0	+	0	0	0	■	-	+	-	+	-	+	0	+	0	0	0
7b	Publicly financed support: scarcely funded	0	0	0	0	0	0	0	0	0	0	0	0	-	■	0	0	0	0	0	0	0	0	0	0
8a	Agricultural production and harvest: substantial share is used for non-food industrial purposes	+	-	0	0	+	-	0	0	+	0	+	0	+	0	■	-	+	0	+	0	+	0	0	0
8b	Agricultural production and harvest: minor share is used for non-food industrial purposes	-	+	0	0	-	+	0	0	0	+	0	+	0	0	-	■	-	+	-	+	-	+	0	0
9a	Industrial production and processing: substantial share uses bio-based raw materials	+	0	0	0	+	0	0	0	+	0	+	0	+	0	+	-	■	-	+	-	+	-	0	0
9b	Industrial production and processing: minor share uses bio-based raw materials	-	+	0	0	0	0	0	0	0	0	0	0	0	+	-	+	-	■	-	+	-	+	0	0
10a	Competition between fossil-based and bio-based polymers (production): substantial share is substituted	+	0	0	0	+	0	0	0	+	0	+	0	0	0	+	-	+	-	■	-	+	-	0	0
10b	Competition between fossil-based and bio-based polymers (production): substitution only for certain market	-	+	0	0	-	0	0	0	0	+	0	+	0	0	-	+	-	+	-	■	-	+	0	0
11a	Competition between fossil-based and bio-based polymers (use): use of bio-based polymers with	+	0	0	0	0	0	0	0	+	0	+	0	0	0	+	-	+	-	+	-	■	-	0	0
11b	Competition between fossil-based and bio-based polymers (use): use of bio-based polymers remains	0	+	0	0	0	0	0	0	0	+	0	+	0	0	-	+	-	+	-	+	-	■	0	0
12a	Waste management: advantages of bio-based polymers are fully exploited	+	0	+	-	+	0	+	0	+	0	+	0	0	0	+	0	+	0	+	0	+	0	■	-
12b	Waste management: bio-based polymers performs poor	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	■

3.2 Specific influencing factors by types of polymers

To illustrate the specific obstacles and promoters of the different polymer types, the main influencing factors are shown as bullet points in the following sections. These factors should be assumed to be specific to the polymer type for which they are listed. Some of these factors are not really specific to one type of polymer, however where this factor was emphasised in an interview it is also mentioned here.

3.2.1 Starch

The total volume of starch polymers is expected to continue to grow while the total market share will drop as other bio-based polymers such as PLA gain market presence (Novamont, 2003b). As already mentioned, in 2002 the market for starch bioplastics was about 25,000 t.p.a., about 75-80% of the global market for bioplastics (Degli Innocenti and Bastioli, 2002). It is predicted that in 2010, starch polymers will hold 50 % or more of the market for bio-based polymers (Novamont, 2003b).

Obstacles

There have been a number of good technical and economic breakthroughs achieved in the last years and starch polymers are able to compete with traditional materials in some limited areas; however major efforts are still required in the areas of material and application development to move from a niche- to a mass market. The following obstacles may be identified as contributing to the relatively modest commercial success of starch polymers to date and the concomitant lack of public awareness (SINAS, 2003):

- **Expense**- the starch based products such as compost bags and picnic utensils that have been proposed for commercialisation are considerably more expensive than the oil based plastic alternatives limiting their public acceptance (cost sensitivity);
- **Aesthetics**- products made from starch have not attained required levels of aesthetic appeal, i.e. rough or uneven surfaces on starch sheets, non-isotropic cell distribution within starch foam resulting in brittleness;
- **Manufacturing**- the relatively unsuccessful efforts to manufacture starch based products utilising injection and compression moulding equipment and extruders/die configurations whose performance is optimised for oil based plastics or food production rather than the different process requirements of thermoplastic starch;
- **Chemistry**- unavailability of starch based materials whose resistance to water can be regulated from completely water soluble to water resistant;
- **Density**- the absence of extrusion based methods for the manufacture of starch foam products whose density more closely approaches styrofoam; and
- **Marketing**- the absence of a variety of highly visible starch based products that highlight, promote and educate the public to the particular advantages of using starch, e.g. renewable resource, water solubility/biodegradability, non-toxicity, volatility to non-toxic components (CO_2 and water).

Drivers

Drivers which have already been realised to a certain extent include (Degli Innocenti and Bastioli, 2002) include:

- Low cost of starch;
- Starch available in large quantities;
- Biodegradable: composting bags, fast food tableware, packaging, agriculture, hygiene;
- Incinerable;
- Renewable;
- Other specific requirements: breathable silky films for nappies; chewable items for pets; biofiller for tyres.

Those that would be favourable or in some cases are required for further market development (Degli Innocenti and Bastioli, 2002):

- Cost structures that consider disposal cost as integral part of total cost (eg. reduced VAT for materials with a low environmental impact);
- More focus/importance given to environmental impact assessment of biodegradable polymers;
- Promotion of composting as a waste management initiative and as a low cost recovery method, particularly in agriculture;
- Biological treatment of biowaste should include compostable polymers in the list of suitable input materials for composting;
- Packaging directive should include compostable packaging.

3.2.2 PLA

All lactic acid on world market is ‘captive’ (Cargill Dow, 2003). At full capacity, the Cargill Dow lactic acid plant will provide 180,000 t.p.a. of lactic acid as feedstock, which is about two thirds of the total world production of lactic acid, currently 280,000 t.p.a.

Obstacles

- **Cost**- Cost of lactic acid due to fermentation costs must fall to a level on par with the price of ethylene for PLA to attain true competitive status in the engineering polymer market. High lactic acid costs for prospective market entrants due Cargill Dow’s partnership agreements with Cargill and Purac;
- **Manufacturing**- Process energy requirements are high; there are still significant energy savings to be realised. Conversion technologies (e.g. sheet extrusion, thermoforming) need to be further refined. Credibility with converters needs to be built up;

- **Environmental**- Lack of waste management and composting infrastructure means that in many countries including the US, China and Japan, PLA's biodegradability is not a useful feature in practice. This often conflicts with a country's own laws in this regard; e.g. Taiwan has passed legislation against fossil fuel plastics which it cannot meet due to lack of waste handling infrastructure; China has no composting infrastructure and is not willing to pay the price.
- Genetically modified (GM) maize issue may be an obstacle for entering the European market. This is particularly the case for the UK where there is no sales plan for PLA because retailers (e.g. TESCO) are following a very cautious policy, thereby avoiding any risk of adverse publicity.
- GMOs in fermentation technology also is/will be an issue.
- Lack of awareness of industry, retailers and public of PLA in general and of its bio-based and biodegradable nature in particular.

Drivers

- **Cost-** The raw material (carbon source to fermentation process) is in oversupply resulting in a stable or downward trend in commodity price; e.g. US corn.
- New lactic acid technologies are leading to substantial price reductions.
- Economies of scale, as demonstrated by Cargill Dow plant (it is possible for a PLA plant to have a capacity of 200 kt.p.a., but this is the design limit. As a comparison: PE plants are typically about 250 kt, PS 180 kt, PET 120-180 kt).
- **Manufacturing**- PLA is compatible with conventional thermoplastic processing equipment.
- Performance can be matched at lower cost; e.g. PLA – cellophane.
- Retailers are showing interest: Albert Hein, Aldi, Sainsbury's, Co-op, Esselunga, Iper, the German retailer cooperative Rewe and beer festivals in Belgium and the Netherlands.
- Improvements in the fermentation of lignocellulosics will bring down costs as well as reduce environmental impact.
- **Environmental**- Consumers are willing to pay more for environmentally sound products. Cargill Dow's retail experience in the US and EU shows this to be the case.
- Biopolymers have been allowed in the green bin in Germany since Oct '02.
- German DSD (Duales System Deutschland) for packaging waste stipulates a lower fee for polymers with more than 50% renewable feedstock content.
- European Waste Packaging Directive 2006 requires that 25% of plastic packaging waste be recycled.

3.2.3 PHA

Procter & Gamble (P&G, 2003) sees the greatest potential for demand in Asia, both developed and developing countries: China uses large tonnages of starch/PE film for agricultural purposes. There is a huge potential market for a PHA compounded resin (e.g. with starch) in this market if significant reductions in the price of PHA can be achieved. Taiwan originally planned to rely on incineration for plastics waste disposal but major problems were encountered due both to the high capital re-investment costs associated with high temperature incinerators and due to the lack of infrastructure for utilising or converting the waste energy. As a result, the Taiwanese government decided not to incinerate plastics. With a population of 28 million and a consumption rate of 2.4 plastic containers per person per day, there is obviously a sizeable market for biodegradable packaging should prices become more competitive.

According to P&G the key factors which will determine the market potential in 2010 and beyond for PHAs are production costs decreasing to USD 1.50 per kg; composting infrastructure (both commercial and home based) expanding and the trend toward disposables continuing for developing economies.

Obstacles

- **Cost-** Scale of production is too small.
- A real value chain doesn’t exist: Commercialisation of fermentation-based plastics requires integration of an entirely new value chain, comprised of previously unassimilated industries – agriculture, fermentation, polymers, compounders, and plastics converters. This is why governments, interest groups, researchers and marketers play such a vital role in forming viable value chains for these new bio-based products .
- Cost, risk of change: An industry accustomed to near-zero variability and a low rate of new polymer class introduction will have to re-learn processing and converting conditions. An industry accustomed to ever-decreasing prices due to overcapacity and near-zero ability to pass on material cost increases due to intense competition will have to re-learn “value selling”. This is why leading marketers and converters must be involved as polymers are developed and commercialised to ensure the best materials are produced and the final products have meaningful advantages.
- Lack of Critical Mass: Without an adequate array of properties from a variety of biopolymers, end-users will not be able to convert a critical mass of their products. Without a critical mass of end products, it will be difficult for composters to obtain a critical mass of appropriate input and justify new capacity investments to take advantage of growing array of compostable products. Without the critical mass of infrastructure in place, communities will be unable to obtain the anticipated advantages used to justify the higher material costs. This is why collaboration amongst biopolymer producers is so important, and why collaboration with the composters and other disposal industries is critical.

- **Manufacturing**- Whereas the currently-employed fermentation technology is close to being optimised, according to P&G the final processing still needs a lot of work.
- **Environmental**- There is an ongoing debate within Europe and elsewhere over both genetically-modified organisms and transgenic crops, market and consumer acceptance of PHA produced in this way and issues related to obtaining approval in Europe for plant-based PHA. Shell, Dupont and DSM, among other major companies, are not investing in crop-based production of polymers as they believe the venture is too risky and/or problematic. (DSM, 2003).
- Production of PHA generates a large amount of biomass waste: about 5 kg of raw material is required to obtain 1 kg product (Novamont, 2003b). Thus, there is an issue of both low conversion and waste management.
- **Miscellaneous**- Approval for contact with food. As PHAs are directly produced in microorganisms rather than synthesised from a monomer, approval is much more complex and costly than with standard polymers, for which approval can be granted based on the quantity and toxicology of the monomer. (Biomer, 2003).
- P&G are already licensed to produce Nodax® inside transgenic crops, but this remains a technical challenge in the sense that it is not really practicable to make a whole lot of different types of Nodax® in the plant (system becomes too complex: think of cultivation of a different crop species for each polymer, harvesting, separation and purification of intracellular polymer from bio-mass, testing and certification of each variant, etc.). A more feasible scenario is to produce one ‘workhorse material’ (such as PHB) in crops then proceed with further biochemical processing to obtain desired copolymer formulations[20].
- An additional barrier is created by the need for year-round feedstock to maximise the utilisation of capital. Since crops are harvested in a short time window, storage is required, which is expensive and can lead to significant degradation of the material (Anex, 2004).
- Licensing can cause loss of momentum. Example given of the P&G licensing of process technology to Kaneka Corp: Kaneka has a pharmaceuticals focus and is geared to production of durables. This approach clashes with that of P&G (consumer goods, short life/disposable). P&G now prefers to keep up the momentum in the development of Nodax® by staying involved; to this end joint ventures are favoured.

Drivers

- **Manufacturing**- PHB formulations are similar to PP or PE-HD but are easier to mould, have a better surface and thinner walls.
- Alkaline digestibility and flushability are convenience factors of interest to the production of single-use consumer goods.
- Ongoing improvements in microorganisms (chiefly through genetic engineering) enabling better yields from cheap feedstocks.

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[20] P&G’s prediction is that plant-based ‘growth’ of Nodax® will be achieved within three years. This timeframe seems optimistic compared to that proposed by Bohlmann (2004) suggesting commercialisation by 2010 at the earliest.

- **Environmental**- Biodegradability is seen as a solution to plastics waste disposal problem.Renewable resource-based
- **Miscellaneous**- Inquiries and new initiatives from customers/suppliers (20 requests out of 6000 hits per week) on Nodax® website drives innovation.

3.3 Price projections

Numerous factors determine the market price of a polymer, among them the price of other materials it can substitute (e.g. glass or metals), the processing costs and the demand. For polymers with similar properties (e.g. bio-based PTT and petrochemical PET) and provided that there are no policy measures in place that support or impede a certain type or group of polymers, the price per mass unit of material plays is a key determinant for the success or the failure in the marketplace. Since for standard polymers as used in bulk applications, there is a strong competition among the producers the market price is closely related to the production cost. The production cost, in turn, is determined by the expenses related to raw materials and auxiliaries, utilities, the capital stock, labour and other expenditures.

Being the key raw material, the oil price has a considerable share of the overall cost: for polypropylene, for example, the price of naphtha accounts for 24 % of the market price of the polymer (see Figure 3-6). While the oil price cannot (or hardly) be influenced by companies they strive to reduce their cost by improving their energy efficiency and energy mix and by minimising their cost related to the other inputs. By making use of learning and scaling effects over more than five decades the polymer industry has brought down polymer prices substantially (see Figure 3-8).

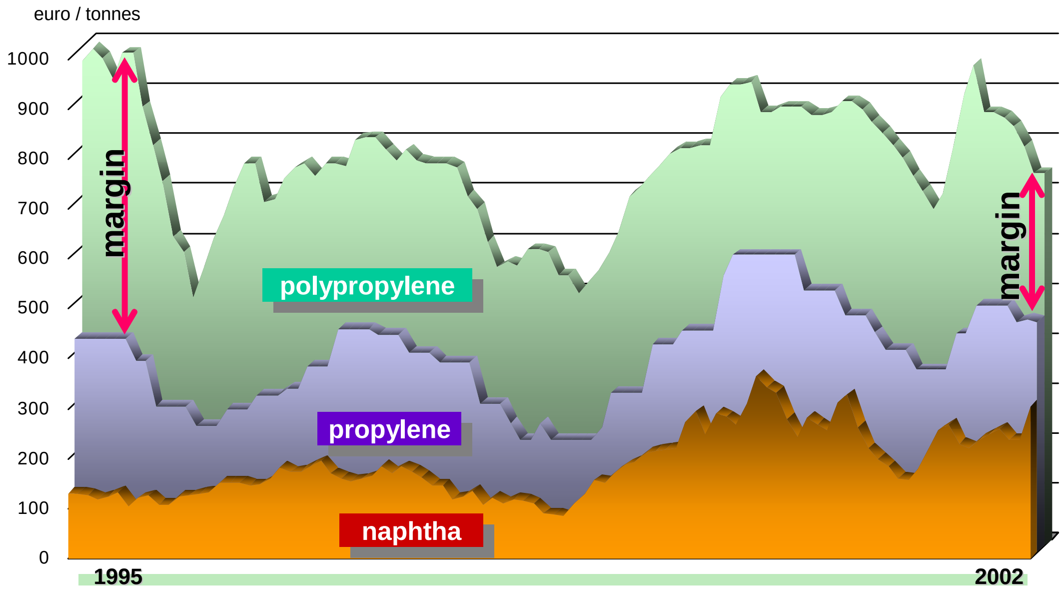
The hypothesis of this section is: for the production of bio-based polymers learning effects can be considered, which are similar to petrochemical polymers.

In a first step, the dynamic of progress for an average petrochemical polymer is analysed (Section 3.3.1). For the calculation German production and price figure are used, because long time series with prices from the fifties are not available for Europe. The error made should not be serious, because the technologies are the same and the German and the European market price are equal.

In a second step, the experience curve is applied for projecting the price of petrochemical polymer for the year 2030 (Section 3.3.2).

Technology developed is partly directly used for the production of bio-based polymers. However, to a considerable extent new technology must be developed. In Section 3.3.3, the experience curve of Section 3.3.1 is adapted and used for projecting prices of bio-based polymer.

Figure 3-6 Prices for Polypropylene, Propylene and Naphtha in Western Europe 1995 to 2002



Source: VKE, 2003

3.3.1 Estimations of Experience Curves for the Production of Petrochemical Polymers in Germany

3.3.1.1 Introduction

Learning effects, which are crucial components in the development of technologies, are often described via *experience curves*. These experience curves show the empirical relationship between unit costs of production and accumulated production or capacity. Typically, a decline in costs can be observed as more experience in production is gained. As a result, learning from higher production translates into improved efficiency in the form of higher performance or lower costs. Experience curves are not based on rigorous theoretical concepts but rather an ad hoc empirical representation. Following Berndt (1991) an experience curve can be expressed by Equation (1):

$$(1) \quad c_t = c_0 n_t^{\alpha} e^{u_t}$$

where c_t stands for real unit production costs at time t, n_t stands for the cumulative production or capacity up to time t and u_t is a (random) error term which is usually assumed to capture non-systematic variations in the production process. That is, all other factors on unit costs which are not captured by n are assumed to be stochastic. The parameter α is the elasticity of unit costs with respect to cumulative volume. It is typically negative and gives the percentage decline in unit costs from a one percent increase in cumulative production. The rate of cost decline is called *progress ratio* (PR):

$$(2) \quad PR = 2^{\alpha}$$

For example, a progress ratio of 0.8 which corresponds to α = -0.33 implies that a doubling of production results in a decline of unit costs to 80 percent of its previous level. The progress ratio is used to compare experience curves of different technologies. Alternatively the *learning rate* can be applied which is just 1-PR.

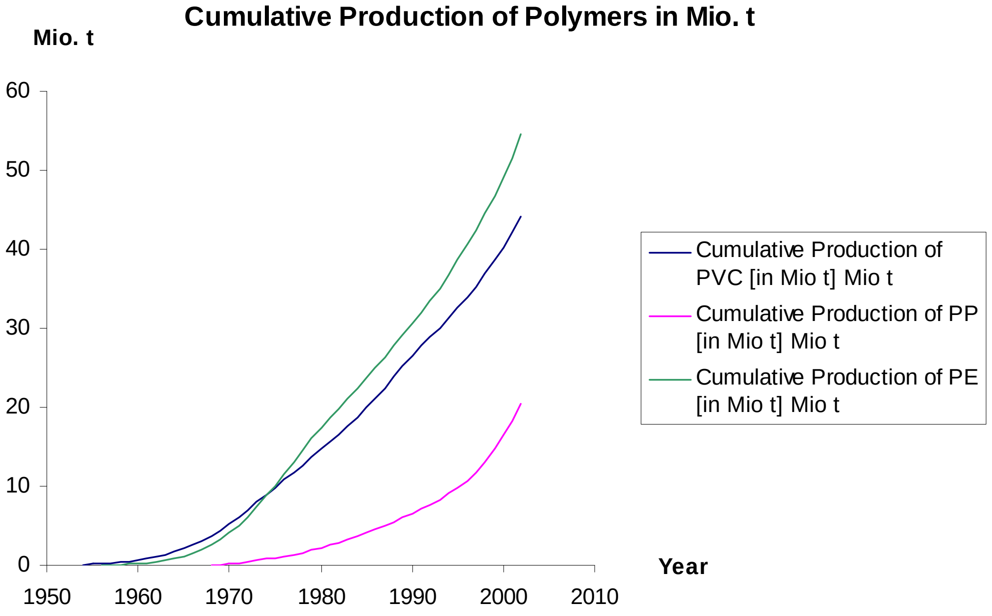
In Section 2 various estimation results for experience curves are presented for individual polymers. In Section 3 an average polymer is constructed and experience curves are estimated for this average commodity.

3.3.1.2 Model Specification

Experience curves will be estimated for three conventional polymers: polyvinyl chloride (PVC), polypropylene (PP) and polyethylene (PE).[21] Estimation results will then be used to construct experience curves for bio-polymers.

Cumulative production of PVC, PP and PE in Germany is displayed in Figure 3-7.

Figure 3-7: Cumulative production of PVC, PP and PE in Germany in million tonnes



Data source: VKE (2003), Statistical Federal Office (2003), ki (2003)

For each polymer, econometric techniques (Least Squares Estimation) will be applied to the following *conventional regression equation*[22]:

$$(3a) \quad \ln(c_t) = const. + \alpha \ln(n_t) + u_t$$

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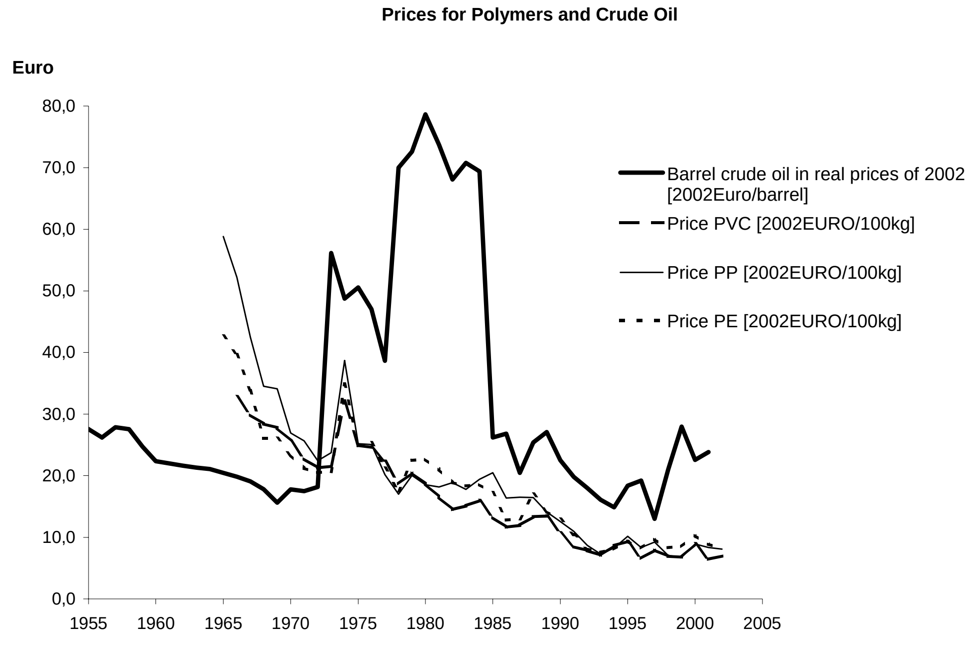
[21] There was not sufficient data available for running similar regressions on polystyrene.

[22] Equation (3) is derived by taking the natural log in Equation (1).

Since no data are available on production costs, observable market prices which are shown in Figure 3-8 are used as proxies (VKE, Statistical Federal Office, ki: kunststoff-information). Using market prices as left-hand-side (LHS) variables is quite common in estimating experience curves, but this approach implicitly assumes a fairly constant relation between production costs and market prices over time.

For the estimation of experience curves for conventional polymers, it is important to account for the price fluctuations of crude oil which is the major input in the production of polymers. The real price path for crude oil is also shown in Figure 3-8. Clearly, the price development of the polymers and crude oil are highly correlated although the second oil crises at the end of the 1970s had less of an impact on the market prices for polymers in Germany than the first oil crisis in 1973. Figure 3-8 also shows the impact of the high-interest policy of the US Federal bank in the early 1980s which resulted in an increase of the US-dollar in international currency markets. The price paths of the polymers and the oil price in Figure 3-8 suggests that during the oil crises and in the early 1980s producers of conventional polymers may not have been able to pass on the additional input costs to their customers in the same way as before and after these periods. The actual specification of the model accounts for these effects.

Figure 3-8: Prices for Polymers and Crude Oil (Base year 2002)



Data source: BP, VKE, Statistical Federal Office, ki

First, to capture the impact of crude oil prices on the costs of production for polymers, the (natural logs of) *relative prices* are used as left-hand-side variables in the conventional regression Equation (3a). Second, to address the impact of the oil crises in the 1970s and the high US dollar in the early 1980s, a dummy variable was introduced for the period 1974-1985.[23] The modified regression equation then becomes

$$(3b) \quad \ln(c_t) = const. + \alpha \ln(n_t) + \delta D + u_t$$

where c_t is the relative price, n_t is the cumulative production of polymer and the dummy variable D assumes a value of one for the years 1974-1985 and zero otherwise[24]. As before, u_t is a random error term.

3.3.1.3 Estimation Results for Petrochemical Polymers

Equation (3b) was estimated econometrically (Ordinary Least Squares) for the production of polyvinylchloride, polypropylene and polyethylene in Germany for the years 1969 to 2002. Estimation results are displayed in Table 3-2.

Table 3-2 Regression results for experience curves of polymers

Equation	Constant	Cumulative Production	Dummy	Number of Observations	R^2	Progress Ratio
PVC	14.77** (0.87)	-0.64** (0.05)	-0.76** (0.09)	34	0.86	0.64
PP	8.85** (0.33)	-0.311** (0.02)	-0.79** (0.07)	34	0.98	0.81
PE	12.46** (0.46)	-0.50** (0.02)	-0.61** (0.06)	35	0.92	0.71

Standard Errors are given in parenthesis ( )
** parameter estimates individually statistically significant at least at the 1 % level

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[23] Results of other model specifications (e.g. using data on the capacity of installations to explicitly account for economies of scale) which yield statistically insignificant parameter estimates, are presented in the draft interim report to this project.

[24] Since a strong US Dollar and a high world market oil price have the same effects on the price of oil in Germany the use of just one Dummy variable to capture both effects is justified.

All parameter estimates show the expected signs and are significant at the 1 % level or better. In particular, introducing dummy variables to capture the effects of the oil crises and the high dollar value proved useful. Without the dummies, the estimates for the parameter on cumulative production may have been biased. The portion of the variation in relative prices which can be explained by the regression (R^2) is rather high and ranges between 86 % for PVC and 92 % for PE. Figures 3-9 to 3-11 provide a graphic representation of the estimation results for equation (3a) using double-logarithmic scales. This representation implies that any distance along the axes is directly proportional to the relative change in the cumulative production and price and corresponds to the interpretation of the parameter estimates as elasticities. The experience curve is then displayed as a straight line. A double-logarithmic representation, rather than using regular scales, reflects that after impressive initial improvements there are steady and continuous improvements which should always be regarded as relative to previous achievements (IEA p. 108).

The steeper the observed curve, the larger are the learning effects. Thus, the estimation results suggest that the production of PVC is associated with higher learning effects than PE and PP which exhibits the smallest learning effects of the three polymers analysed. The progress ratios associated with the experience curves range between 64 % for PVC and 81 % for PP. Compared to analyses of experience curves for other technologies,[25] the implied cost decreases for PP and PE are at the higher end of the distribution.[26]

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[25] For overviews on estimated learning curves for energy technologies see for example International Energy Agency (IEA) (2000): Experience Curves for Energy Technology Policy, IEA, Paris, or McDonald, A. and Schrattenholzer, L. (2001): Learning Rates for Energy Technologies, *Energy Policy* 29, p. 255-261.

[26] It is rather clear that for the estimation of experience curves for a technology which - like polymerisation - is used globally, it would be more appropriate to also use data for world production and world prices. Unfortunately no complete time series data set for the production of PVC, PE and PP (with figures for years before 1970) is available. In addition, no world or reference price for these polymers exists, but rather prices for certain large markets (e.g. Western Europe). Also, market prices include country-specific taxes, subsidies, or factor costs. For these reasons, we use in our analysis regional figures from Germany for production and prices which is a common approach in other scientific analyses of experience curves such as for wind energy or photovoltaics. However, learning effects which result from increased production abroad and thus affect polymer prices in Germany are not specifically accounted for. In fact, using German production data instead of world production data may result in a so called "measurement error" which leads to biased parameter estimates.

Nevertheless, available, but incomplete world production figures were used together with the prices for Germany (=Western Europe) to estimate experience curves. As expected, the estimations for the Learning Rates decrease and the learning rates increase (PVC: 0.64 to 0.77, PE: 0.71 to 0.78, average polymer: 0.66 to 0.78). Only for polypropylene the difference was relatively small (0.81 to 0.82) since the production share of Germany remained fairly constant over the last 30 years.

Figure 3-9 Estimated experience curve for PVC production in Germany

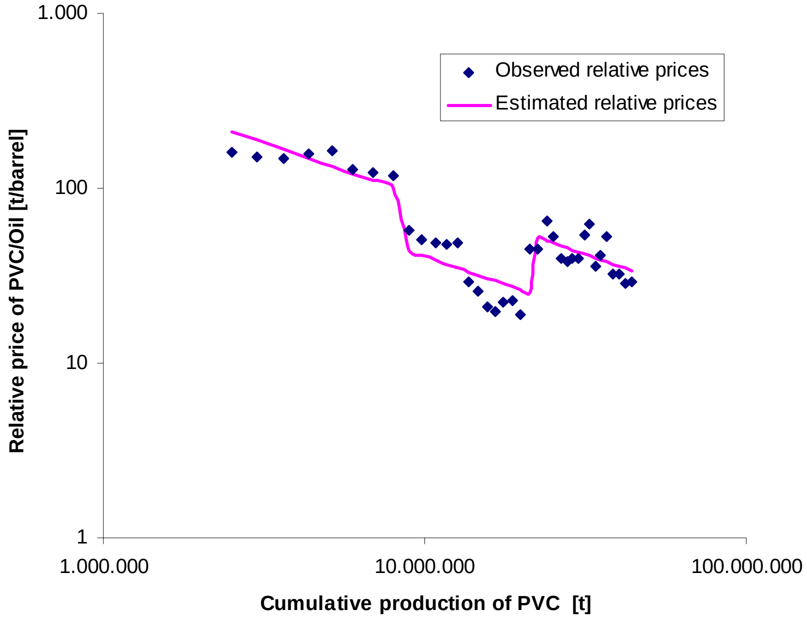


Figure 3-10 Estimated experience curve for PP production in Germany

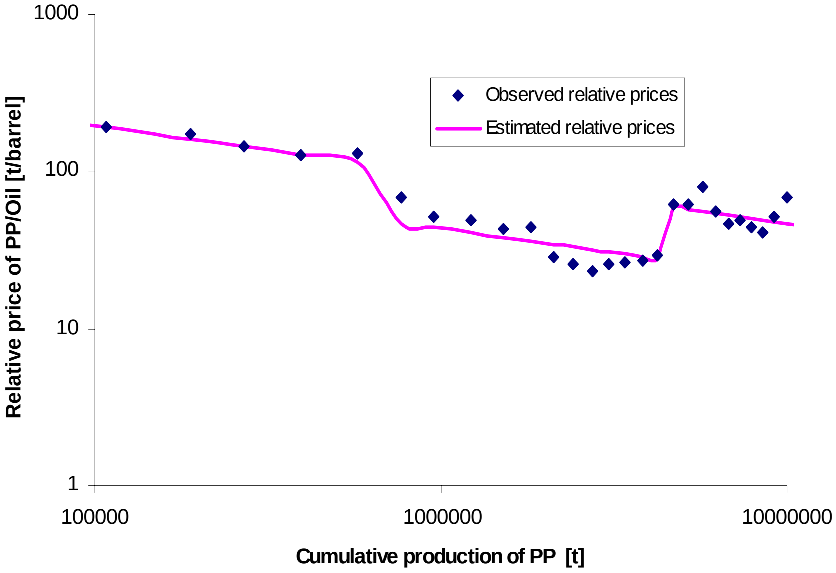
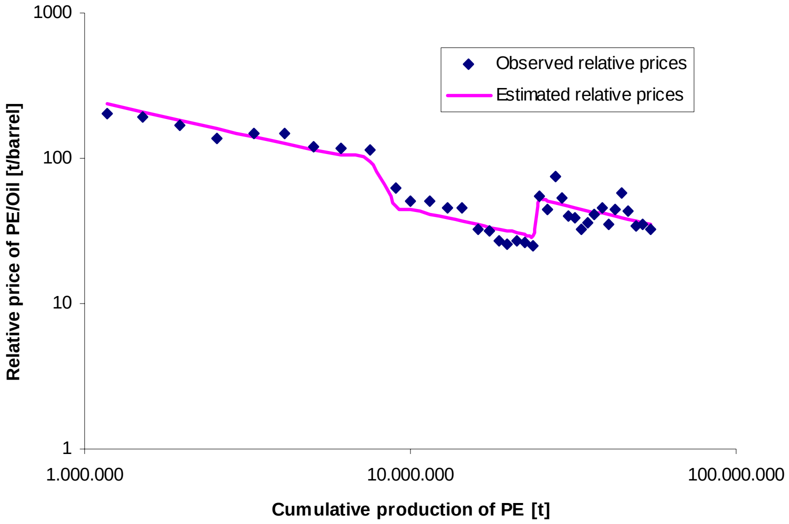


Figure 3-11 Estimated experience curve for PE production in Germany



3.3.1.4 Experience Curve for an Average Polymer

In this section estimation results for an average polymer are presented. Instead of estimating a single equation for each polymer, for projections of the general polymer market, it was considered appropriate to generate a single average polymer.

To construct the values for an average polymer a time path for an average price (real) is generated from the price paths of the individual polymers using contemporary production as weights. Then, equation (3b) is estimated with the average price as the (Left Hand Side) LHS-variable. On the RHS, cumulative production which is just the sum of the cumulative productions of the individual polymers, and the real crude oil price entered the regression equation. It should be noted that the number of observations is smaller than for the individual polymer estimations since only those periods could be included were data for all three polymers was available. So, some information gets lost when estimating the equation for the average polymer compared to the estimations for the individual polymers. Estimation results for the average polymer appear in Table 3-3.

Table 3-3 Regression results for experience curves for an average polymer

Equation	Constant	Cumulative Production	Dummy	Number of Observations	Corrected R^2	Progress Ratio
Average Polymer	14,7** (0.86)	-0.604** (0.048)	-0,63** (0,08=	32	0.84	0.66

Standard Errors are given in parenthesis ( )
** parameter estimates individually statistically significant at least at the 1 % level

3.3.1.5 Experience Curve for a Technical Polymer

Following a suggestion we obtained at the projects expert workshop, we tried to estimate an experience curve for a technical polymer like e.g. PET, PA. However, availability of production data for these polymers was very poor. Fortunately, BAYER AG provided data for polycarbonate enabling an estimate to be made for an experience curve for one technical polymer. Regression results appear in Table 3-4 and the associated experience curve is shown in Figure 3-12. The estimated progress ratio for polycarbonate is 0.94, which is substantially higher than for the polyolefines in the previous subsection. Table 3-4 and Figure 3-12 reveal that the estimation for PC is not as good as the estimations for PVC, PP, and PE in terms of goodness of fit R^2).

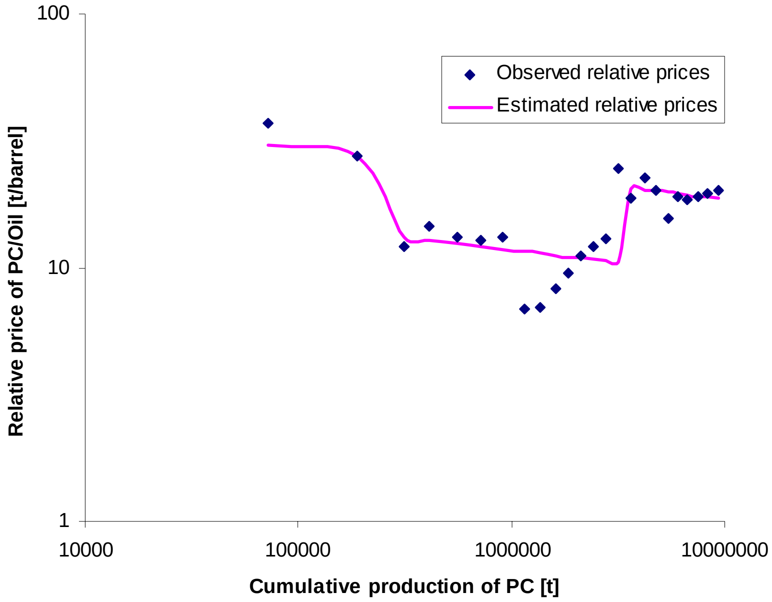
Table 3-4 Regression results for experience curves of polycarbonate

Equation	Constant	Cumulative Production	Dummy	Number of Observations	Corrected R^2	Progress Ratio
PC	3.84** (0.38)	-0.10** (0.05)	-0,69** (0.12)	21	0.61	0.93

Standard Errors are given in parenthesis ( )

** parameter estimates individually statistically significant at least at the 1 % level

Figure 3-12 Estimated experience curve for PC production



3.3.2 Price projections for petrochemical polymers

The four petrochemical polymers are in different stages of their life cycle. PC is a technical polymer with more complex production stages and not so large capacities in one plant. PP has been enjoying rapidly rising demand and its capacities have been expanded considerably in the recent past. In contrast, PE is a relatively mature polymer with moderate growth rates. Finally, PVC is widely used especially in the construction sector. However, due to disadvantages in waste management and increased public concern about the associated environmental and health effects it has lost market share in several other application areas, among them packaging and some consumer products such as toys. As a consequence, all four polymers have different progress ratios. By use of the curve for an average polymer (for PVC, PE and PP) these differences are largely levelled out[27].

The application of the average curve derived in Section 3.3.1.4 to petrochemical polymers yields a price decrease of 46% over the next two decades[28]. Halving of the prices of conventional polymers in 20 years does not seem impossible if one considers that they have declined by nearly a factor of 5 in the last 35 years. This comparison can be made in more detail by studying the historical annual price decrease of petrochemical polymers. Depending on the period chosen, polymer prices have dropped by 1.2% p.a. to 3.6% p.a. (data for an average petrochemical polymer).[29] If extrapolated to 2030, the lowest value (1.2% p.a.) leads to a total price drop of 36%.

In order to assess the quality of the results of our regression analyses a few independent calculations were made. In a first step, we were interested in the share of the total production cost that is directly related to energy prices (via feedstock and energy cost). We estimated this share at 17%, which is somewhat below the value derived from Figure 3-6 for polypropylene. We consider this estimate to be rather uncertain; the real value may lie in the range between 7% and 23%. Our first conclusion is that this share is consistent with the outcome that the prices for conventional polymers will halve (provided that the oil/energy prices do not change too much; see also below).

Further sensitivity analyses with various levels of oil prices are shown in Figure 3-13. The projections used for petrochemical polymers originate from the Base Case scenario of the IPTS "Clean Technologies Project" (Phylipsen et al, 2002). Oil prices were linearly increased from \$25/bbl in 2002 to \$30/bbl in 2030 in the Low Oil Price Scenario, to \$35/bbl in the Reference Scenario, to \$50/bbl in the High Oil Price Scenario and to \$100/bbl in the Very High Oil Price Scenario. According to these results learning and scaling more than overcompensate the effects of rising crude oil prices. Only for very high oil prices polymer prices exceed the value of 2002. In all other cases petrochemical polymer prices drop – in the Reference Scenario even by substantial 38 % to 2020. It must be discussed whether these results are considered plausible by the polymer industry. If not, this has important consequences for the comparison with bio-based polymers for the following two reasons: firstly, for the obvious reason that the results for petrochemical polymers serve as a benchmark for the

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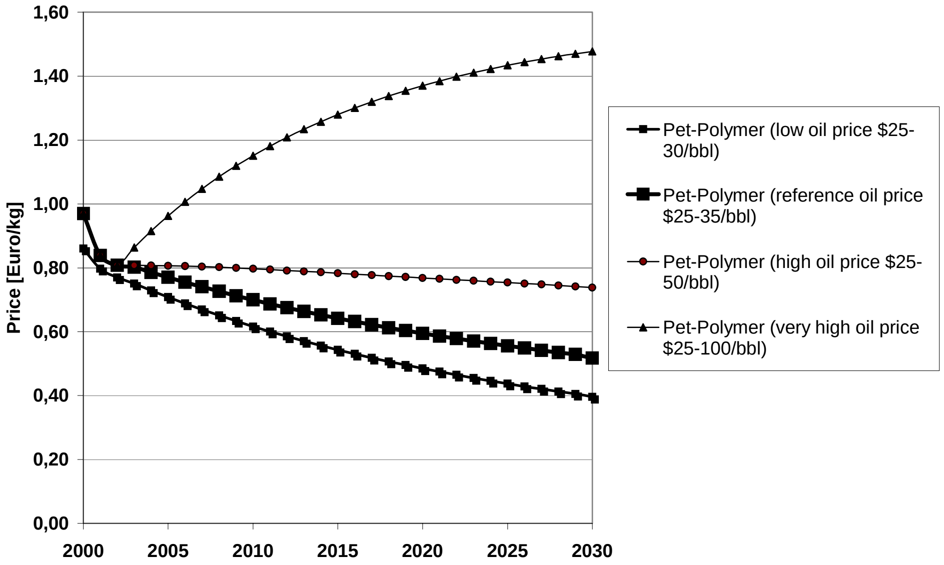
[27] PC was not used for the average polymer calculation, because the available time series for prices and production volumes are very short.

[28] Assuming a constant oil price.

[29] In more detail for an average polymer (weighted median of cumulated production of PE, PVC, PP): -2.3% p.a. for the period 1968-2002; -1.2% p.a. for 1980-2002; -1.5% p.a. for 1986-2002; -3.6% p.a. for 1995-2002.

bio-based polymers; and secondly since the relationship found in the regression analysis for petrochemical polymers has been applied to bio-based polymers (see further discussion below).

Figure 3-13: Sensitivity analyses for petrochemical polymer prices as a function of oil prices



3.3.3 Price projections for bio-based polymers

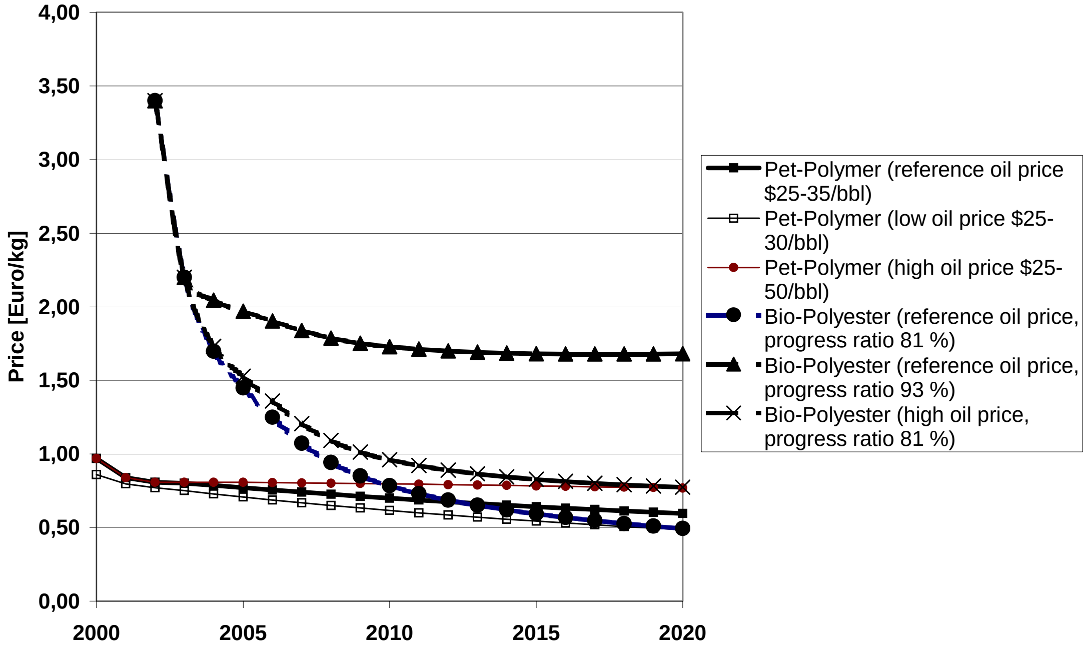
The experience curves calculated for the petrochemical polymers in Chapter 3.3.1 are not directly applicable for bio-based polymers. Direct use of the equations derived above would fail for many reasons. One reason is that the market price of bio-based polymers today already includes some of the learning effects which are incorporated into the equations for petrochemical polymers: part of the technology developed for petrochemical polymers is also used for bio-based polymers. This refers, for example, to standard unit processes of chemical engineering in the area of product separation. Another aspect to consider is that faster technological progress is (likely to be) made for biotechnological production processes. This means that it is not a straightforward task to derive the real progress ratio for bio-based polymers from the experience made in the petrochemical sector. Related to this is the fact that many decades of experience in chemical engineering allows a much faster scale-up compared to what was possible in the 1930s and 1940s. This explains why the producers of bio-based polymers expect a large growth of capacities in the next three decades: the doubling rates for the production of bio-based material are higher than those for PVC, PE or PP.

Some of these problems can be circumvented by a basic engineering approach using flowsheet methods such as ASPEN. However, this requires an in-depth knowledge that is only found in developers. Still, there remain some uncertainties, especially if applying innovative technology, for example biotechnological processes or new ways of chemical modification (of starch). Also the yields of the different process stages and the quality needed for subsequent processing are not clear, factors on which the market price is dependant.

So we have to adapt the equation for petrochemical polymers. To consider the more complex production processes we use the same learning factor as for polycarbonates (0.93) and polypropylene (0.81), which is a relatively new polymer. The biomass feedstock price is kept constant.

Using this equation, the price of both petrochemical and bio-based polymers comes into the same range within 20 years (see Figure 3-14). The result is heavily dependent on changes in the oil price and the relationship between fossil fuel costs and biomass costs.

Figure 3-14 Projection of the Price for bio-based polyesters and petrochemical polymers



3.4 Market projections for bio-based polymers

In view of the outcome of the preceding section, the expectations of the producers of bio-based polymers were used as starting point for the projections of production volumes. The following **approach** has been taken:

I) In a first step, the companies' expectations of the market development were compiled and compared. This data generally refers to the supply of polymers to the market, either as a total or for the main types of polymers.

II) In a second step, information on the market demand by application areas was collected and compared to the supply data. Partly this information was also provided by companies, partly it is based on own simple estimations.

III) In the third step, an attempt was made to develop plausible time series for production in the EU that take into account supply and demand expectations and also unit size of large plants.

In **Step I** only dispersed pieces of information have been identified. These can be summarised as follows:

- Under the **European Climate Change Programme (ECCP)** estimates were made for the production of bio-based polymers (and other bio-based materials) until 2010: According to these estimates bio-based polymers are expected to grow in the European Union from 25 kt in 1998 to **500 kt in 2010 without supportive Policies and Measures (P&M) and to 1000 kt with P&Ms**.

- The **International Biodegradable Polymers Association & Working Groups (IBAW, Berlin)** follows this view and projects a further growth of bio-based polymers **in the EU to 2-4 million tonnes until 2020** (Käb, 2002).[30] Half of this total is expected to consist of compostable products while the other half would then be durables.

- The **Japanese Biodegradable Plastics Society (BPS)** has prepared projections for the market of biodegradable polymers in Japan. By 2010, the total consumption is estimated at 200,000 tonnes of which 187,000 are expected to be bio-based (BPS, 2003). These projections have been made based on company announcements and confidential information that was made available to the BPS. According to personal communication with BPS (represented by K. Ohshima, 2003) BPS' projection can be considered as conservatively realistic and could well be on the lower side. To make comparisons with projections for the EU this total can be scaled up by multiplication with the ratio of total polymer use in the EU and in Japan or by multiplication with the ratio of inhabitants. Due to the similar specific consumption of plastics (in kg per capita) in Japan and in the EU the outcome of the two approaches is very similar, amounting to a rounded **equivalent of 600 kt of bio-based polymers for the EU by 2010**. This hence **supports the estimate made by the ECCP** (500 kt in 2010 without P&Ms and 1000 kt with P&Ms).

- **IBAW** also prepared a **global projection** for the production of bio-based polymers that are biodegradable (see Figure 3-15). This forecast was made based on company announcements (partially confidential) for investments in the short term. In first instance one might expect this data to present only a subset of all bio-based polymers (namely the biodegradable ones). However, this is not the case since all major bio-based polymers that are currently on the market or that are about to be commercialised are biodegradable at the same time. Exceptions such as polymers with suppressed biodegradability (as possible in the case of PLA) were not excluded in Figure 3-15. Another reason why IBAW's projection is of direct use without any corrections is the exclusion of natural fibre composites, which are also outside the scope of this study.

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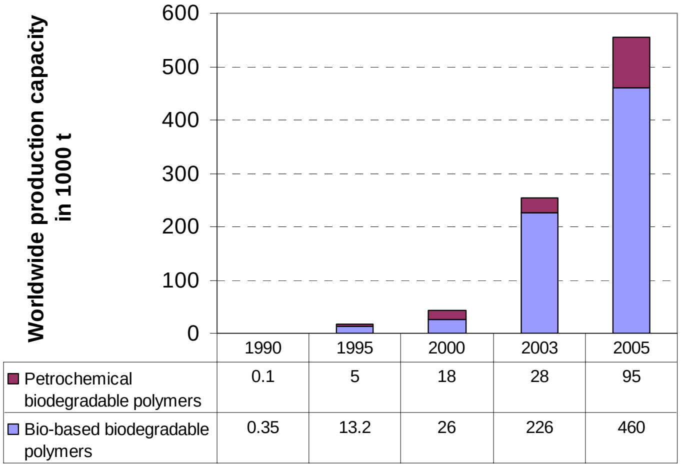
[30] Total "biopolymer" market in the EU: 3-5 million tonnes of which 70-80% are expected to be bio-based.

For individual polymers, some insight was gained from the interviews with producers of bio-based polymers.

- Novamont agrees with the projections prepared under the ECCP (see above) and expects that **half or more than half of all bio-based polymers produced in 2010 will be starch polymers, i.e. 250 to 500 kt** (Novamont, 2003b).
- By 2010, **Cargill Dow plans** to have **two additional PLA plants** of a similar capacity as the one in Nebraska (140 kt p.a. capacity). This would lead to a combined production capacity of 500,000 t.p.a. Cargill Dow plans to build their next facility wherever the market develops and in combination with best manufacturing economics (Cargill Dow, 2003). It seems most likely that this will either be the case in Asia or in Europe.
- Hycail intends to have a full-scale plant with **50-100 kt p.a.** capacity by the end of 2006 and to start up a **second plant by 2010**. There seems to be firm plans to have at least one plant in the EU.
- According to Galactic (Galactic, 2003) recent estimates put the PLA market **for films and non-woven/fibers products alone** at about 122,000 t p.a. in 2003-2004, 390,000 t p.a. in 2008 and reaching **1,184,000 to 1,842,000 t p.a. by 2010**. In their view such estimates are very realistic and probably even on the pessimistic side. Arguments given are the continued very small share relative to the total polymer sector and the economies of scale that are being made use of with new large-scale facilities. They also refer to a price/market model developed by the PST Group which clearly shows that for markets of about 900,000 t p.a. the selling price of PLA compares favourably with petrochemical plastics used by the packaging industry.
- **Showa Highpolymer**, one of the key producers of succinic acid, has estimated current and future market volumes in the EU and worldwide (personal communication with Y. Okino, 2003). It is anticipated that succinic acid production will increase from today 20 kt in the EU (55 kt worldwide) to 100 kt by 2010 (worldwide: 450 kt). Showa Highpolymer plans to shift their succinic acid production from petrochemical to bio-based in the short term. If this production route proves to be superior this may mean that many – possibly even all – new succinic acid plants will be using bio-based feedstocks.

Figure 3-15: Worldwide projections prepared by IBAW on the development of bio-based and petrochemical biodegradable polymers (Käb, 2003b)



	1990	1995	2000	2003	2005
■ Petrochemical biodegradable polymers	0.1	5	18	28	95
□ Bio-based biodegradable polymers	0.35	13.2	26	226	460

The only detailed piece of information that could be identified in **Step II** is a compilation by Proctor & Gamble (P&G) on the **worldwide current market potential for biodegradable polymers by application areas** (see Appendix 1), which was prepared to estimate the potential market for Nodax (PHA). The total amounts to 1.17 million tonnes p.a. worldwide, of which the fast food industry accounts for 60%. Total food packaging[31] represents around 1 million tonne or more than 80% of the total volume identified. With the focus being on biodegradable products, the potentially very large area of bio-based synthetic fibres (e.g. PLA) and applications in the automotive and the electric/electronic sector have not been taken into account; moreover certain products that are not interesting for Nodax such as loose-fill packaging material have been excluded. The market potential outside the food sector is substantial as, for example, Cargill Dow's estimate for the PLA market in the fibre sector shows (50% of the total market, see Table 2-11); IBAW has expressed similar expectations according to which around 50% of the bio-based polymers will be used for durables by 2020. Using Proctor & Gamble's expectation as a starting point this leads to the conclusion that the **current total global market potential for bio-based products should be in the range of 2 million tonnes or possibly beyond**. A value **of more than 2 million tonnes globally** may be realistic if one considers that P&G's market estimate did not include all options for using bio-based polymers in packaging (including food) but only those that are of particular interest for Nodax and that there are also interesting markets in the area of durable products apart from fibres.

In Table 3-5, an **estimate for the market potential of bio-based polymers in the EU** has been made by combining moderate estimates of the market share by application area with the total polymer volumes. This yields a total total market potential for bio-based polymers of **2 million tonnes in the EU**. Combining the same estimates of the market share by application with the total volume of the polymer market in 2020 results in a total volume of bio-based polymers of **around 3 million tonnes**. This is a conservative estimate in the sense that it does not take into account the increase of market shares due to technological progress and market development and neither does it include the use of bio-based polymers in tyres.

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[31] Including fast food packaging, flexible plastic food containers (oily snacks), thermoformed products (for dairy products).

Table 3-5: Market potential of bio-based polymers in EU-15 countries by 2000 and 2020

	Year 2000			Year 2020		
	All polymers$^{1)}$	Market potential of bio-based polymers		All polymers$^{1)}$	Market potential of bio-based polymers$^{2)}$	
	million t	% of pchem.	million t	million t	% of pchem.	million t
Packaging	17.7	5.0%	0.9	27.6	5.0%	1.4
Building/construction	8.0	0.50%	0.04	12.5	0.5%	0.1
Automotive	3.4	15.0%	0.5$^{3)}$	5.4	15.0%	0.8
Electric/electronic	3.3	5.0%	0.2	5.2	5.0%	0.3
Agriculture	1.1	3.0%	0.03	1.7	3.0%	0.1
Other	11.3	3.0%	0.3	17.6	3.0%	0.5
Total	44.9	4.4%	2.0	70.0$^{4)}$	4.4%	3.1

1) Petrochemical and bio-based (bio-based nowadays less than 0.1%); split by application area according to APME.

2) Purely accounting for growth of polymer production as a whole; without taking into account larger market potential shares due to technological progress and market development.

3) Independent estimate for bio-based polymers without the use in tyres:
0.15 t/(passenger car) * 20% bio-based * 17 million cars = 0.5 million tonnes

4) Value for 2020 from the Clean Technologies project (Phylipsen et al., 2002)

In **Step III**, an attempt was made to develop plausible time series for production in the EU that take into account supply and demand expectations and also unit size of large plants. Table 3-6 shows two scenarios which are named "WITHOUT P&M" and "WITH P&M". The totals are closely linked to the ECCP estimates for 2010 and follow similar dynamics thereafter. As the percentages in brackets show, bio-based polymers are expected to account for a maximum of 2.5% of the EU production of petrochemical polymers by 2020. The totals are broken down into starch polymers and polyesters. Starch polymers are assumed to account for as much as half of total production until 2020. The expected developments are displayed graphically in Figure 3-16 (until 2010) and Figure 3-17 (until 2020).

Table 3-6: Specification of the projections for the production of bio-based polymers in PRO-BIP, scenarios "WITHOUT P&M" and "WITH P&M"

All values in kt	Starch polymers, WITHOUT P&M	Starch polymers, WITH P&M	Polyester/ PUR/PA, WITHOUT P&M	Polyester/ PUR/PA, WITH P&M	**Total, WITHOUT P&M$^{1)}$**	**Total, WITH P&M$^{1)}$**	*For comparison*		
							ECCP	*IBAW*	*BPS' projection for Japan, scaled up to EU-15*
EUROPE									
2002	25	25	0	0	**25** (<0.1%)	**25** (<0.1%)	-	-	
2010	250	500	250	500	**500** (0.9%)	**1000** (1.7%)	*500/1000$^{2)}$*	*500/1000$^{2)}$*	*600*
2020	375	750	500	1,000	**875** (1.25%)	**1750** (2.5%)	-	*2000-4000*	
WORLDWIDE									
2002	110	110	30	30	**140**	**140**			
2010	375	750	900	1,750	**1,275**	**2,500**			
2020	550	1,125	1,650	3,050	**2,200**	**4,175**			

1) Percentages in this column represent shares of bio-based polymers relative to petrochemical polymers. According to the "Clean Technologies Project" (Phylipsen et al., 2002) the production of petrochemical polymers in Western Europe according to the Base Case Scenario amounted to: 40.4 Mt (1998), 44.9 Mt (2000), 57.4 Mt (2010), 70 Mt (2020), 81 Mt (2030)

2) Without and with Policies and Measures (P&M)

3) Based on 187 kt bio-based polymers in Japan in 2010 according to BPS (2003). Applied scale-up factors: i) Scale-up factor, thermoplastics consumption EU/Japan = 3.4; ii) Scale-up factor, population EU/Japan = 3.0.

Figure 3-16: Development of bio-based polymers in the EU until 2010 – Scenarios “WITHOUT P&M” and “WITH P&M”

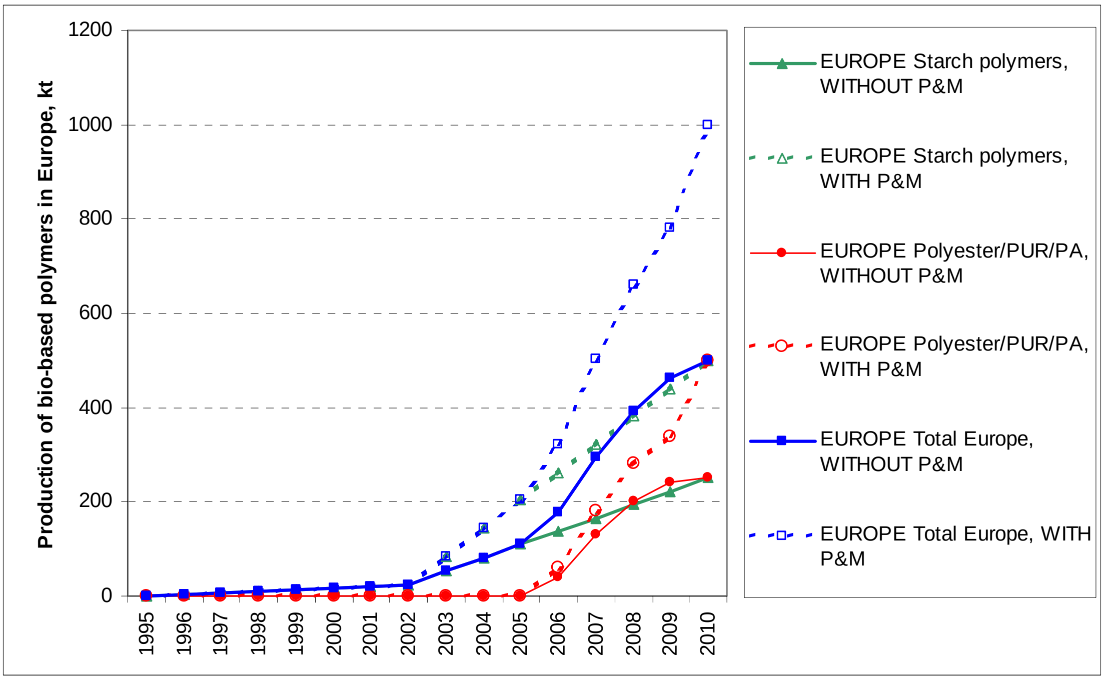
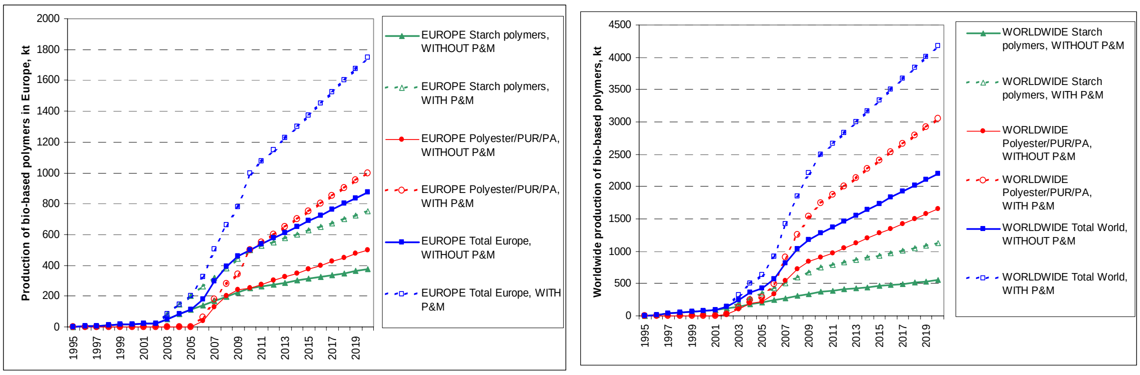


Figure 3-17: Development of bio-based polymers in the EU (left) and worldwide (right) until 2020 – Scenarios “WITHOUT P&M” and “WITH P&M”



The projected volumes according to Table 3-6 and Figure 3-16 to Figure 3-17 are in line with the plans/expectations described earlier, for example with those expressed by Novamont, Cargill Dow and Hycail. The *current* global market potential of least 2 million tonnes that was derived above from Proctor & Gamble’s analysis, supports the worldwide data for 2010 in Table 3-6. The EU market potential estimates according to Table 3-5 indicate that the estimates in Table 3-6 for Europe by 2020 are plausible or possibly even underestimated. Also according to Galactics’s view (1.18-1.84 million t.p.a. by 2010 for films and non-woven/fibers products alone) and IBAW’s expectation for 2020 (2-4 million t for all bio-based) the EU values for 2020 in Table 3-6 seem to be underestimated. It must be recalled here that this report is based on information on *commercialised and emerging* bio-based polymers. Other bio-based polymers which are currently in an earlier phase of R&D are not taken into account even though some of them might be produced on a respectable scale towards the end of the projection period of this report (year 2020). Bio-based chemicals that are not used for polymer production (e.g. solvents, lubricants and surfactants and other intermediates and final products) are outside the scope of this report; if they develop favourably, this also could reinforce the growth of bio-based polymers.

In order to account for possible breakthroughs and a more dynamic development a **third scenario called “HIGH GROWTH”** is introduced. As shown in Table 3-7 this scenario follows the same trajectory until 2010 as the scenario “WITH P&M” but continues to expand at a high rate until 2020 especially due to enhanced growth of PLA and the advent of PTT, PBT, PBS, PUR and PA – or at least some of them – in the marketplace. The HIGH GROWTH scenario is backed by the higher estimate for market potential in Table 3-7 (3.1 million tonnes).

The per-capita-production values in Table 3-7 point out once more the enormous difference in scale between bio-based and petrochemical polymers: **Today 66 grams of bio-based polymers are produced per capita and year, while the yearly per-capita production of petrochemical polymers is around 180 kg.** The per-capita values for 2020 show that the quantities are reasonable (and “imaginable”) even in the HIGH GROWTH case provided that bio-based polymers make their way into products of everyday life (compare Table 2-33).

Table 3-7: Total production of bio-based polymers in the PRO-BIP scenarios “WITHOUT P&M”, “WITH P&M” and “HIGH GROWTH” in the EU

		Bio-based polymers			Pchem.polymers
		Total, WITHOUT P&M	Total, WITH P&M	Total, HIGH GROWTH	"Base case"
Total production in kt	2000	**25** (<0.1%)	**25** (<0.1%)	**25** (<0.1%)	44,900
	2010	**500** (0.9%)	**1000** (1.7%)	**1000** (1.7%)	57,400
	2020	**875** (1.25%)	**1750** (2.5%)	**3000** (4.3%)	70,000
Production in kg/(cap*a)	2000	0.066	0.066	0.066	119
	2010	1.3	2.6	2.6	152
	2020	2.3	4.6	7.9	185

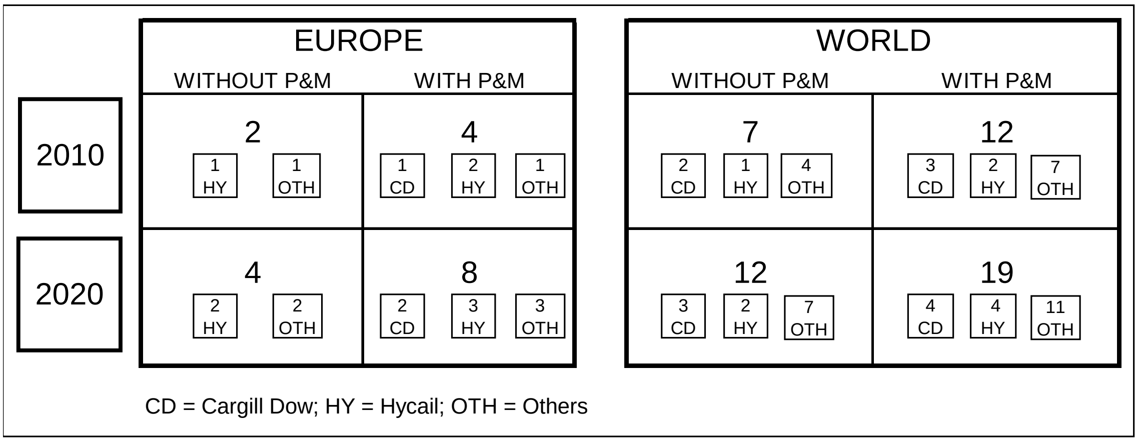
Percentages in brackets represent shares of bio-based polymers relative to petrochemical polymers (see footnote of preceding table).

In the following an attempt is made to substantiate the projections given above, partly by relating them to the size of production plants and partly by studying selected application areas somewhat more deeply. The focus is on the scenarios “WITHOUT P&M“ and “WITH P&M“ while it seems too speculative to discuss the possible developments by groups of polymers for the scenario “HIGH GROWTH“. The discussion begins with bio-based polyesters, polyurethanes and polyamides, which are dealt with as a group, and continues with starch polymers. Cellulose polymers are not taken into account in the remainder of the report since they are not expected to play a key role in the future.

Bio-based polyesters, polyurethanes and polyamides

There seems to be consensus that **bio-based polyesters/PUR/PA** will only have a chance to compete on bulk polymer markets if they are produced in world-scale plants of similar size as those for petrochemical polyesters. Cargill Dow’s facility in Nebraska is an example for such a world-scale plant, with an annual production capacity of 140 kt p.a. Future unit sizes for large-scale plants may range between 100 kt p.a. to 200 kt p.a. (and possibly even beyond) for a product like PLA (for other products such as PBS the plants may be smaller). This means that the total volumes according to Table 3-6 can be translated into a (rather limited) number of plants in Europe and worldwide. Such an attempt has been made in Figure 3-18, with an **indicative** allocation to the possible key players Cargill Dow, Hycail and others. The names of the players and the plant capacities just mentioned show that within the group of bio-based polyesters, PLA is seen to have a key role, at least in the first phase. Other bio-based polyesters, polyurethanes and polyamides may, however, also be part of the “game“ and may enter the scene after some delay. In particular, this could be the case for PTT, PBS/PBSA and PUR and also for PHA and PA if the technological progress is fast enough. The number of plants producing bio-based polyesters/PUR/PA in scenario “WITH P&Ms“ in 2010 has been assumed to be identical with the number of plants without P&Ms by 2020. The limited number of actors and facilities in both scenarios makes this area amenable to well-targeted policies.

Figure 3-18: Bio-based polyesters - Number of plants and indicative allocation to players



	EUROPE		WORLD	
	WITHOUT P&M	WITH P&M	WITHOUT P&M	WITH P&M
2010	2 1 HY 1 OTH	4 1 CD 2 HY 1 OTH	7 2 CD 1 HY 4 OTH	12 3 CD 2 HY 7 OTH
2020	4 2 HY 2 OTH	8 2 CD 3 HY 3 OTH	12 3 CD 2 HY 7 OTH	19 4 CD 4 HY 11 OTH

CD = Cargill Dow; HY = Hycail; OTH = Others

Starch polymers

For starch polymers, the quantities projected are comparable to those for bio-based polyesters until 2010 and somewhat less in the following decade (Table 3-2). An important difference is that to date, starch polymers have been produced in relatively small facilities. For example, new production lines started up by Novamont in 1997 had production capacities of 4 kt and 12 kt respectively. At the time of writing, it was unknown to the authors of this report whether a scale-up by at least a factor of l0 would be technically feasible and economically attractive. While deliberations about the plant size do not provide much additional insight for starch polymers, considerations about the application areas seem more helpful: Given the fact that the strong efforts and the commercial success of the starch polymer business over more than a decade have led to relatively small production capacities (in Europe 30 kt for Modified Starch Polymers, 70 kt including Partially Fermented Starch Polymers) it seems obvious that **totally new outlets** are required in order to reach the overall quantities according to Table 3-2. The use of starch polymers **as filler and partial substitute for carbon black in tyres** is the only potential large-scale outlet that is known to the authors of this report and that could play such an important role.

Data from various sources have been used to estimate the use of carbon black for tyres in the EU, among them the UN production statistics (UN, 2002) and dispersed data quoted from reports and given on websites. Since the available information is conflicting, the estimates of carbon black produced for tyres in the EU are subject to substantial uncertainties. The following data have been used:

- EU production of carbon black: 1.3 million t.p.a., possibly up to 2 million t.p.a.
- Share of carbon black used for tyres: 50-70%, average value 60%.

Based on this data the amount of carbon black produced for tyres in the EU is estimated at 900 kt (average value), with the uncertainty ranging between 650 kt and 1250 kt. The amount substituted is not only related to the carbon black production but to the volume of tire production. Moreover, fillers are being traded and the supply of a new advantageous filler type could, in principle, allow large exports of material processed elsewhere. Finally, only the use in tyres has been looked into while there may be other similarly interesting (industrial) rubber products that lend themselves to substitution. For these reasons the wide range of carbon black production (650-1250 kt; medium 900) may not even capture the real situation. Finally it has been assumed that starch polymer fillers can substitute 20% or 50% of the carbon black used in a tyre (Table 2-7). This results in starch polymer outlets in the EU of

- **180 kt p.a. (range: 100-250 kt.p.a.) for a substitution rate of 20%**
- **450 kt p.a. (range: 250-600 kt p.a.) for a substitution rate of 50%.**

The full exploitation of these substitution potentials is estimated to take two rather than one decade provided that the technology and the products prove to be clearly advantageous. The comparison with the starch polymer projections for 2020 according to Table 3-2 shows that **half of the starch polymer production – possibly even three quarters – could be devoted to tyre production.** The remaining half to quarter would then be used for proven application areas where it would partly compete with other bio-based polymers. It can be expected that specific advantages allow substantial growth rates also in these established areas (possibly for loose fills or clam-shells). This has not been investigated since detailed market research is beyond the scope of this study.

The “HIGH GROWTH“ Scenario

While very little information is available on the market prospects of PTT, PBT, PBS, PUR and PA, a few considerations may help to put the assumptions made in the “HIGH GROWTH“ Scenario into perspective:

- PTT, PBT, PBS and PA are now all being produced from petrochemical feedstocks. While this poses particular pressure on the bio-based counterparts a competitive edge in manufacturing or product properties could translate into substantial returns in the future. If the bio-based equivalents enter the market at the right time they can benefit from the market introduction via their petrochemical equivalents and enjoy the particularly high growth rates around the inflexion point of market penetration.
- Polyamides (PA) are characterised by their large number of processing steps and the resulting high production cost and environmental impacts. A bio-based production route with a modest relative advantage (in % of energy savings, cost savings etc.) could therefore mean a decisive advantage for its producer, allowing fast market introduction.
- The same argument holds for polyurethanes (PUR). Similar to PA, it is mostly used in high-value application areas (especially furniture, apparel and automobiles; see Figure 2-21) with relatively good substitution potentials.

Caveats

As explained earlier the values presented in Table 3-6 and 3-7 and in Figure 3-17 and 3-18 are largely based on information originating from manufacturing companies. This may lead to projections that are too optimistic.

An attempt was made to gain a better understanding of the situation by collecting more information about the experience made by Cargill Dow. Cargill Dow could serve as a valuable case study since other players producing new bio-based polymers might make a similar experience in the market deployment phase. The idea was to draw some first conclusions by

- comparing the scheduled start-up to full capacity (Section 2.2.5) with the actual development and by
- gathering information from polymer processors about their experience.

However, only a limited amount of information could be collected on these two points. There are rumours that the market development is behind schedule but it was not possible to obtain any information from Cargill Dow on this point. According to an interview with a polymer processor using PLA (Treofan, Germany) the market may indeed be developing slower than anticipated. It was not possible to identify the current status since this would require reliable information about the purchases of *all* clients of Cargill Dow (worldwide) which is hardly manageable in practice. However, even if this information were available, the lack of precedence cases would make it difficult to arrive at judgements: After all, a new bio-based polymer is being introduced to the market in large quantities and it is therefore not surprising that technical and acceptance problems are encountered. Among these are the appearance of pure PLA film the electrostatic charge of PLA film which causes problems when using it as windows for envelopes and the lack of biodegradable printing inks that fully meet the consumers' expectations (personal communication, Treophan, 2003). These problems seem resolvable, albeit with (some) additional time and expenses. The potential consequences are unknown. It is also unclear how other application areas such as fibres are developing.

To summarize the situation concerning Cargill Dow, it is impossible to identify at this stage whether any major delay exists and if so, whether it may be serious in terms of further market development (compare Figure 3-18). With regard to the projections for bio-based polymers in general it should be kept in mind that the (unavoidable) use of information provided by producers **may lead to projections which are too optimistic** (in terms of growth and final levels). This could even be the case for the scenario "WITHOUT P&M" where the lowest growth rates of all scenarios have been assumed. High uncertainty regarding the production volumes is obviously implicit in an emerging industry. It has been addressed in the **"Note of caution"** at the beginning of this report and will be taken into account in the concluding chapters of this report (Chapter 5 and 6).

4. Assessment of the environmental and socio-economic effects of bio-based polymers

4.1 Goal and method of the environmental assessment

The main purpose of this chapter is to assess what the environmental effects would be of substituting bio-based polymers for petrochemical polymers on a large scale. The assessment is conducted for the scenarios developed in Chapter 3. **Two perspectives** are taken. Firstly, the savings of fossil fuels, the effects on greenhouse gas emissions and the consequences for land use are studied. Secondly, it is analysed whether the lower specific environmental impact of bio-based polymers (e.g. kg $CO_{2,eq.}$ per kg of polymer) can (over-)compensate the additional environmental impacts caused by expected high growth in petrochemical plastics.

It is good practice for environmental analyses and life cycle assessments (LCA) to make the comparison "**as close to the end product as possible**". The rationale behind this good-practice rule is that certain parameters at the end-use level may decisively influence the final results. Such parameters may concern

- materials processing, where the amount of material required to manufacture a certain end product might be higher or lower than for petrochemical polymers
- transportation, which can be substantial for end products with a low density such as loose fill packaging material
- the use phase, where consumer behaviour can play a role (e.g., in the case of compost bins without a bin liner where the way of cleaning the bin has a large influence on the overall environmental impact)
- the waste stage where logistics and recycling processes can be tailored to a specific product or product group.

If strictly applied, the good-practice rule of conducting the analysis at the end-use level would necessitate an infinite number of comparisons because all possible end products would need to be assessed and compared (from the TV housing to the toothpick package). This is obviously not manageable. For this reason, a simple and uniform **functional unit** must be chosen. The most commonly applied approaches are to conduct a comparison for

- one mass unit of polymer in primary form (1 kg or 1 tonne of pellets or granules) or
- one volume unit of polymer in primary form (1 litre or 1 m^3 of pellets or granules).

In this study, one mass unit of polymer in primary form has been chosen as the basis of comparison (functional unit) since this approach is most frequently used. Such comparative analyses at the level of polymers in primary form have the advantage that they provide a first impression about the environmental advantages or disadvantages. For example, if the environmental performance is not attractive at the material level (pellets, granules), there is a good chance that this will also be true at the product level.

However, it must be borne in mind that the comparison may be distorted if, at the end-use level, decisive parameters differ between bio-based and petrochemical polymers.

The environmental analyses conducted in this study refer to two types of **system boundaries**, which are represented by two approaches:

- The **cradle-to-factory gate** approach covers the environmental impacts of a system that includes all processes from the extraction of the resources to the product under consideration, i.e. one mass unit of polymer in this study.
- The **cradle-to-grave** approach additionally includes the use phase and the waste management stage. Since one mass unit of polymer in primary form has been chosen as the basis of comparison in this study, the use phase (including further processing to an end product and its use) is excluded for the sake of simplification. In other words, the use phase is assumed to be comparable for the various types of polymers studied and is therefore omitted.

A cradle-to-grave analysis covers the **entire life cycle** of a product (material) and therefore generally represents the preferred approach. The reasons for applying both approaches in this study will be explained in Section 4.3.

In order to obtain a comprehensive overview of the environmental impacts as many **impact categories** (such as energy use, acidification, eutrophication, human toxicity, environmental toxicity, particulate matter etc.) as possible should ideally be studied. However, some of the impact categories included in a full-fledged LCA study require measurements such as for toxicity and particulate matter. Given the early stage of technology, these parameters are often unknown (e.g. if only small-scale pilot plants are available) or they are kept confidential. Moreover, several impact categories are closely related to energy use – i.e., they are determined by the fuel type (e.g. coal versus natural gas) and the technology of the combustion process (e.g. air preheat) and flue gas scrubbing. Thirdly, different life cycle assessment methodologies and indicators are in use for some impact categories (e.g. for toxicity), making direct comparisons impossible. For these reasons, it was necessary to limit the impact categories covered by this study to the most relevant independent parameters. Against this background, the parameters chosen are **energy use, GHG emissions and land use** (see also Section 4.3).

4.2 Input data for the environmental analysis

The availability of life cycle assessment studies on bio-based materials (including polymers) is still quite limited, which is in contrast to the wide interest in the topic. For all bio-based materials, for which environmental assessments were available, the key results have been presented in Chapter 2. The **availability of relevant data** for conducting comparative environmental assessments, the **quality** of these data and some **general findings** can be summarized as follows:

- **For starch polymers**, several studies have been prepared (e.g., Dinkel et al., 1996; Würdinger et al., 2002 and Estermann et al., 2000). These address exclusively Modified Starch Polymers (Table 2-6 and 2-7), while very little information is available on their use as fillers in tyres (only published as final results, Corvasce, 1999; see Table 2-7) and on Partially Fermented Starch Polymers (only available as internal report).
  The analyses for Modified Starch Polymers deal with pellets (i.e., primary plastics) and/or certain end products, especially films, bags and loose-fill packaging material. Different types of starch polymer blends (different types and shares of petrochemical co-polymers) and different waste management treatment options are assessed (for a comparative overview see also Patel et al., 2003). Exceptions excluded, the results on energy use and GHG emissions from the various studies are consistent, indicating that clear environmental benefits can be achieved and that the environmental impacts related to this group of materials are well understood (one example of an exception is the carbon sequestration related to composting).

  Modified Starch Polymers are the only product group for which results were available for environmental impact categories other than energy use and greenhouse gas (GHG) emissions.[32] Due to the use of different methodologies the comparability of the results for these other indicators is, however, limited.

- **For PLA**, the only publicly available detailed environmental analysis (with a focus on energy use and CO_2) has been prepared by Cargill Dow (Vink et al., 2003; see Table 2-11). Very simple analyses for PLA production from rye and whey have been conducted by the authors of this study (Table 2-12).

- **For PTT**, a preliminary analysis has been performed by the authors of this study (Figure 2-10); as discussed in Section 2.3.1.7 this analysis has shortcomings and needs to be analysed in more depth (this requires the use of confidential data that will become available in the BREW project; BREW, 2003).

- **For PBT,** no verified results on environmental impacts are available; as discussed in Section 2.3.2.7 preliminary results indicate potential energy savings of about 10%.

- **For PBS**, no environmental analysis seems to have been published.

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[32] Results for other impact categories are also available for natural fibre composites and for a thickener for a lacquer (Patel et al., 2003) but these products are outside the scope of this study.

- **For PHA**, several studies are available resulting in a wide range of energy use and CO_2 emissions (Section 2.4.7). While the higher values reported are larger than those for petrochemical polymers, clear benefits also seem to be possible. The fact that PHA prices (see Section 2.4.6) are now clearly beyond those for other bio-based polymers is a consequence of the low yields and efficiencies. These drawbacks need to be overcome as a prerequisite for a wide commercial success. If achieved, the environmental impacts of PHAs can be expected to be in the lower range of those discussed in Section 2.4.7; the use of PHAs would then have clear advantages compared to petrochemical bulk polymers.
- **For PUR** (bio-based), the U.S. United Soybean Board (USB) recently published results. These are complemented by back-of-envelope calculations conducted by the authors of this study.
- **For nylon** (PA; bio-based), no environmental analysis seems to have been published.

Cellulose polymers are not included in the environmental assessment since they are not seen as serious options for substituting large (additional) amounts of petrochemical polymers.

For petrochemical polymers, the APME Ecoprofiles prepared by Boustead (1999-2003) represent a generally acknowledged database that has been used as reference in most cases (exception: lack of data, e.g. for petrochemical PBT).

A particular challenge of this study is the **prospective nature** of the environmental assessment. This means that technological progress needs to be taken into account since it generally contributes to reduce the environmental impacts per functional unit. Ideally, time dependent datasets with a yearly resolution (for the period 2000-2020) would be required for each type of polymer which did not seem reasonable in view of the information available. For this reason it was decided to take a simplified approach; the data compiled in the tables discussed below (Table 4-1 and Table 4-5) is hence considered valid **for both foresight years, 2010 and 2020**. As will be shown later in this chapter this simplified approach can be justified in hindsight.

4.2.1 Data basis for estimating energy use and GHG emission data

The input data used to project the effects of bio-based polymers on energy use and GHG emissions largely originates from the LCA studies discussed in Chapter 2. In a few cases, further adaptations have been made which are explained below.

The values in Table 4-1 refer to the following system boundaries:

- **For energy data, cradle-to-factory gate values** are used. At first glance this may contradict the statement made above according to which an LCA study preferably covers the entire life cycle. However, the use of cradle-to-factory gate energy values does not conflict with this intention in the case of **incineration without energy** recovery[33]. In addition, it must be assumed that the energy use for transportation to waste treatment facility is relatively small; in general it is valid to assume that this is the case. With these additional considerations the energy data in Table 4-1 can also be viewed as **cradle-to-grave values**.
- **For GHG emission data**, cradle-to-grave data are used. In line with the assumption made for energy, **no emission credits due to energy recovery are assumed**. This means that the values in Table 3-4 are calculated by adding up the emissions from the production stage (cradle-to-factory gate) with the emission from full oxidation of the fossil carbon embedded in a (petrochemical) polymer.

The values printed in bold in Table 4-1 have been selected for conducting the prospective environmental assessment for the foresight years 2010 and 2020. Rounded values are being used to indicate that these are rough estimates. Data printed in italics likewise indicate rough estimates. Use of these data for prospective analysis is generally avoided while data printed in bold are used for the projection of the environmental impacts in the next two decades.

The chosen value for **starch polymers** (printed bold) is identical with the value for pure starch polymers (first row of table) since experts in the field are confident that complexing will allow superior material properties without using (petrochemical) copolymers (Novamont, 2003b). For **PLA**, the value for the long term refers to the biorefinery concept where lignocellulosic feedstocks (corn stover) are used as second source for fermentable sugars (in addition to starch) and energy is generated from the lignin fraction.

As discussed in Chapter 3 about half of the future amount of bio-based polymers is assumed to represent starch polymers. It would therefore actually be necessary to have good insight into the composition of the other bio-based polymers because the related energy use and GHG emissions differ widely (see Table 4-1). Since this information is not available rough estimates have been made. Apart from PLA a mixed category “Other bio-based polyesters, PUR and PA” was introduced (see last row of Table 4-1). In line with the categorisation in Chapter 3 this group is intended to include, apart from PUR and PA, all polyesters except for PLA, i.e. PHA, PTT, PBT, PBS, PBSA (and possibly others). For the scenarios “WITHOUT P&M” and “WITH P&M”, PLA has been assumed to be by far the most important bio-based polyesters while the “Other bio-based polyesters, PUR and PA” are considered to be negligible. In the scenario “HIGH GROWTH” (see above), on the other hand, the total additional production beyond the scenario “WITH P&M” is assumed to belong to the category “Other bio-based polyesters, PUR and PA”.

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[33] Also in the case of landfilling. Given upcoming directives for waste containing organic carbon landfilling is, however, not a waste management option for the future.

Table 4-1: Specific energy use and GHG emissions of bio-based and petrochemical bulk polymers

	Energy[1] in MJ/kg			GHG emissions[2] in kg CO_2 eq./kg			Reference for data on bio-based polymer
	Pchem. Polymer[3]	**Bio-based polymer**	**Energy savings**	**Pchem. Polymer[3]**	**Bio-based polymer**	**Emission savings**	
Starch polymers[4]	76	25	51	4.8	1.1	3.7	Patel et al., 1999
Starch polymers + 15% PVOH	76	25	52	4.8	1.7	3.1	Patel et al., 1999
Starch polymers + 52.5% PCL	76	48	28	4.8	3.4	1.4	Patel et al., 1999
Starch polymers + 60% PCL	76	52	24	4.8	3.6	1.2	Patel et al., 1999
Starch polymers, mix today[5]	76	41	35	4.8	2.8	2.0	Estimated for this study
Starch polymers, long-term			**50**			**4.0**	Estimated for this study
PLA - Year 1	76	54	22	4.8	4.0	0.8	Vink et al, 2003
PLA - Whey	76	40	36	4.8	ca. 3.0	ca. 1.8	Vink et al, 2003
PLA - Biorefinery	76	29.2	47	4.8	1.89	2.9	Vink et al, 2003
PLA, long-term			**50**			**3.0**	Estimated for this study
PHA , fermentation	76	81	-5	4.8	n/a	n/a	Gerngross/Slater, 2000
PHB - Heyde, best case	76	66	10	4.8	*3.7*	*1.1*	Heyde, 1998
PH(3B) ex glucose[6]	76	59.2	17	4.8	2.5	2.3	Akiyama et al., 2003
PH(3A) ex soybean[7]	76	50.2	26	4.8	2.3	2.5	Akiyama et al., 2003
PTT (compared to PET)	77	*65*	*13*	5.5	*4.6*	*1.0*	Estimated for this study
PTT, long term			*10*			*1.0*	Estimated for this study
PBT, long term			*(10?)*			*(1.0?)*	Estimated for this study
PBS, long term			*(10?)*			*(1.0?)*	Estimated for this study
PUR - Rigid	99.5	*77.8*	*21.7*	5.9	*5.0*	*0.9*	Estimated for this study
PUR - Rigid, long term			*20.0*			*1.0*	Estimated for this study
PUR - Flexible	103.0	*62.9*	*40.0*	6.0	*4.4*	*1.6*	Estimated for this study
PUR - Flexible, long term			*40.0*			*1.5*	Estimated for this study
Category "Other bio-based polyesters, PUR and PA"[8], long term			***25***			***2.0***	Estimated for this study

Data printed in italics represent rough estimate. Data printed in bold are used for environmental assessment.

[1] Cradle-to-factory gate analysis. Without bio-based feedstock and bio-based energy byproducts used within the process.

[2] Cradle-to-grave analysis. Assuming full oxidation without any credits.

[3] 50% LLDPE + 50% HDPE according to Boustead (1999).

[4] Without petrochemical copolymers

[5] Approximation: 20% pure starch polymers, 10% starch polymers with 15% petrochemical copolymers and 70% starch polymers with 52.5% petrochemical copolymers.

[6] Case 9 in Akiyama et al. (2003)

[7] Case 5 in Akiyama et al. (2003)

[8] This group includes, apart from PUR and PA, all polyesters except for PLA, i.e. PHA, PTT, PBT, PBS, PBSA (and possibly others).

The **energy and emission savings resulting from bio-based polymers** (see Table 4-1) **are rather high** as the comparison with the energy use of other bulk material shows (see Table 4-2): The lower end of energy savings related to bio-based polymers, amounting to 10-15 GJ/t, are in a similar range as the total energy needed to make 2-3 tonnes of cement, 1-2 tonnes of secondary steel (electric arc steel) or of recycled glass, about 1 tonne of paper/board or ca. ½ tonne of recycled aluminium. The relatively high saving opportunities related to bio-based polymers are partly caused by the fact that polymers in general are rather energy intensive to produce (on a mass basis); moreover, some of the processes covered in Table 4-1 account for future technological progress. On the other hand, it has already been shown in other publications that, *in specific terms* (e.g. per mass unit of polymer), bio-based polymers offer very interesting saving potentials already today (see Table 4-3).

Table 4-2: Energy requirements (cradle-to-factory gate; non-renewable energy) for bulk materials

Energy, GJ/t	Öko-Institut[1)]	Worrell et al. [2)]	Hekkert[3)]
Cement (average)	5	3.6 - 6	3.8
Steel			
- Primary	23	20 - 25	
- Secondary	7.4 - 8.3		
Paper/board (average)	10 - 17.5	10 - 20	~10 - 15
Glass			
- Container glass		8	
- Flat glass	~12		
- Glass fibres	36		
- More recycling, container glass		7.2	
Aluminium			
- Primary	182		187
- Secondary	26		

[1)] Data from Öko-Institut, see http://www.oeko.de/service/kea/ files/daten-

[2)] Energy, Vol 19, 1994

[3)] PhD thesis, 2000

Table 4-3: Energy savings and CO_2 emission reduction by bio-based polymers relative to their petrochemical counterparts (exclusively current technology; cradle-to-factory gate) – Results from other studies, compiled in Patel et al. (2003)

	Energy savings		GHG savings	
	MJ/kg bio-based polymer	in %	kg CO_2 eq./kg bio-based pol.	in %
Bio-based plastics (pellets)				
TPS	51	-70%	3.7 (-75%)	-75%
TPS + 52.5% PCL	28	-40%	1.4 (-35%)	-35%
TPS + 60% PCL	24	-35%	1.2 (-30%)	-30%
Starch polymer, foam grade	42	-60%	3.6 (-80%)	-80%
Starch polymer, film grade	23	-55%	3.6 (-70%)	-70%
PLA	19	-30%	1.0 (-25%)	-25%
PHA	-570 to 50	+700% to -35%	n/a	n/a
Printed wiring boards	5	-30%	n/a	n/a
Interior side panel for pass. car	28	-45%	-0.9	-15%
Transport pallet	33	-50%	1.6	-45%

As explained above the data of Table 4-1 are valid for a system “cradle-to-grave” where the waste management technology is incineration without energy recovery. This raises the question how energy recovery could change the picture. Bio-based polymers generally have lower heating values than most petrochemical bulk polymers (Table 4-4). In some cases the difference is negligible (e.g., polyhydroxybutyrate versus PET), while in other cases it is substantial (starch polymers versus PE). In practice, the difference in recoverable heat may be even larger than indicated by Table 4-4 since most bio-based polymers absorb water rather easily. On the other hand, bio-based polymers may have an advantage in energy recovery because they are made of oxygenated compounds that facilitate the combustion process and help to avoid extreme temperatures; the latter can pose serious problems when incinerating petrochemical polymers. While it would require further investigations to determine whether and how this limits the scope of energy recovery, we take a conservative approach in this study by assuming that incineration takes place in waste-to-energy facilities, especially with high energy recovery yields; this is in favour of petrochemical polymers (in energy terms). It is estimated that one quarter of the heating value of the waste is converted to final energy in the form of power and useable heat[34]. The generation of the same amount of final energy from regular fuels in power plants and district heating plants requires only half of the energy input. As a consequence, the credit for energy recovery is equal to half of the heating value. Concerning energy recovery the advantage of petrochemical over bio-based polymers is therefore only half of the difference of their heating values. This case is represented in Figure 4-1 by the vertical line for 50% efficiency for energy recovery. The bold line for polyethylene (PE) serves as a benchmark: all points below this line require less energy throughout their life cycle.

Table 4-4: Heating value of bio-based and petrochemical polymers (heating values calculated according to Boie, compare Reimann and Hämmerli, 1995)

Polymer	Lower heating value, GJ/tonne
Starch polymers	13.6
Polyhydroxybutyrate (P3HB)	22.0
Polyhydroxyvalerate (P3HV)	25.0
Polylactic acid	17.9
Lignin (picea abies)	24.2
China reed	18.0
Flax	16.3
Hemp	17.4
Kenaf	16.5
PE	43.3
PS	39.4
PET	22.1
PVC	17.9

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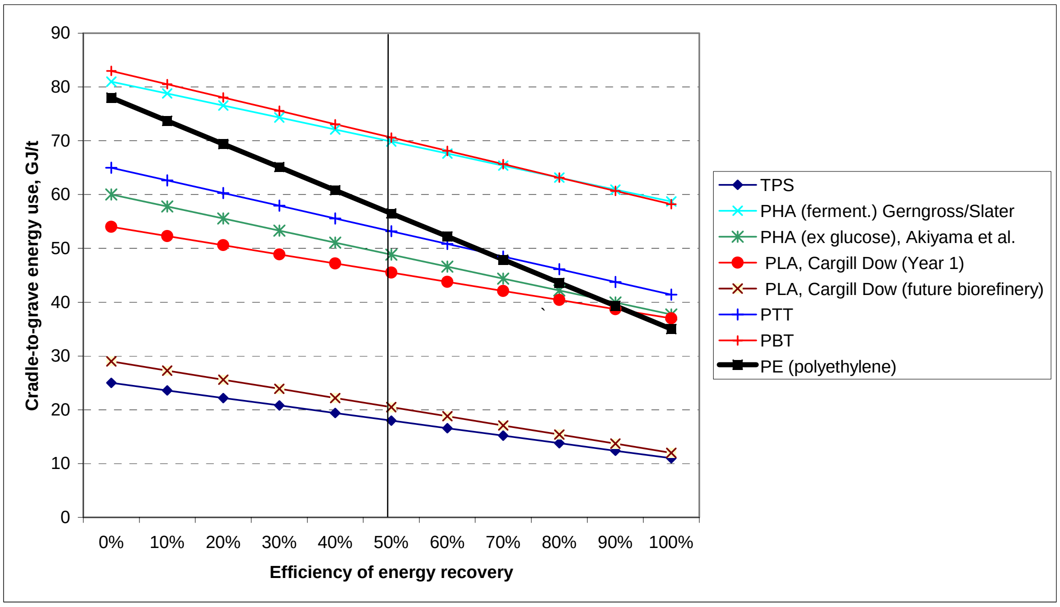
[34] This estimate is based on an analysis for Germany (12% efficiency for both electricity and heat generation from combustible waste; Patel et al., 1999) and for Western Europe (personal communication, Pezetta, 2001). This estimate has also been used in the Clean Technologies project (Phylipsen et al., 1999).

Figure 4-1: Overall energy requirements of polymers (cradle to grave) as a function of the efficiency of energy recovery



4.2.2 Data basis for estimating land use requirements

The LCA studies used contain information about the type and quantity of crop input (number of tons of crop required per tonne of polymer). Using average yields for crop production (compiled by Dornburg et al., 2003) specific land use has been calculated (see Table 4-5). In the preceding section, values printed in bold are used for further calculations. The estimate for the category "Other bio-based polyesters, PUR and PA" (see last row of Table 4-5) is rather uncertain because – due to lack of further data - it has been based on one single data point only (for PH(3B), see preceding row). Since this value (0.6 ha*a/t polymer) is four to six times higher than the values for starch and PLA, underestimation is quite unlikely.

Table 4-5: Specific land use for bio-based and petrochemical bulk polymers

Polymer type	Reference for LCA on polymer	Crop type	Country	Crop yield t/(ha*a)	Crop input t crop/t polymer	Land use (ha*a)/t polymer
Starch polymers[1]	Dinkel et al., 1996	Potato and corn	CH	37.5[2], 12.5[3]	2.23[2] + 0.385[3]	0.09
Starch polymers = 12.7% PVOH	Würdinger et al., 2001	Corn	D	6.45	0.786	0.12
Starch polymers[1]	Estermann et al., 2000	Corn	F	8.2	0.971	0.12
Starch polymers, long term						**0.10**
PLA - Year 1	Vink, 2001 in Dornburg et al., 2003[9]	Corn	USA	9.06	1.74	0.19
PLA - Mitsui 1	Kawashima, 2003	Corn	USA	9.06[9]	2.45	0.27
PLA - corn 2008	Galactic, 2003	Corn	EU-15			0.31
PLA - wheat 2008	Galactic, 2003	Wheat	EU-15			0.48
PLA - sugar beets 2008	Galactic, 2003	Sugar beet	EU-15			0.18
PLA - Mitsui 2 - 0.5corn + 0.5stover	Kawashima, 2003	Corn	USA	9.06[9]	1.29	0.14
PLA - Biorefinery	Vink et al., 2003 combined with estimates based on Aden et al., 2002	Corn	USA	9.06[10]	1.36	0.15
PLA, long-term						**0.15**
PHA - fermentation	Gerngross and Slater, 2000	Corn	USA	7.7	5.06	0.66
P(3HA) ex soybean[4]	Akiyama et al, 2003 (higher range)	Soybean		3.1	7.11	2.29
P(3HB) ex glucose[5]	Akiyama et al, 2003	Corn		7.25[8]	4.15[7]	0.57
P(3HA) ex soybean/lower yield	Akiyama et al, 2003	Soybean		3.1	8.12[6]	2.62
P(3HB) ex glucose/lower yield	Akiyama et al, 2003	Corn		7.25[8]	5.12	0.71
PH(3B), long term (ex glucose)						**0.55**
Category "Other bio-based polyesters, PUR and PA"[11], long term						**0.60**

[1] Without petrochemical copolymers

[2] Potato (data for fresh matter, fm; for all other crops in this table dry matter, dm)

[3] Corn

[4] High fermentation yield; applies to case 5 (and also case 6-8) in Akiyama et al. (2003)

[5] High fermentation yield; applies to case 9 in Akiyama et al. (2003)

[6] According to Akiyama et al., 2003. 1 kg of soybean oil from 5.4 kg of soybeans , Fig.1. PHA yield = 0.7 g/g, Tab.1. 95% PHA recovery, Tab.1.

[7] According to Akiyama et al., 2003. 1 kg of glucose from 1.46 kg of corn , Fig.2. PHA yield = 0.37 g/g, Tab.1. 95% PHA recovery, Tab.1.

[8] Average of range in Dornburg et al., 2003

[9] Using same crop yields as for Cargill Dow case

[10] Using same crop yields as for PLA-year 1 case

[11] This group includes, apart from PUR and PA, all polyesters except for PLA, i.e. PHA, PTT, PBT, PBS, PBSA (and possibly others). Due to lack of other data the value for PH(3B) was used as basis for the estimation.

According to discussions with experts in the field, wheat in Europe could become a similarly or even more important starch source for bio-based polymers as corn (maize). However, most datasets in Table 4-5 refer to the use of corn. The data compiled in Table 4-6 give insight into the extent to which a switch to wheat would influence the land requirements: while the average yield of corn (maize) is 9.1 t/ha (which is in line with the figure for US corn in Table 4-5), the average yield for wheat is substantially lower (5.8 t/ha). As a consequence a switch from corn to wheat would result in 50% higher land requirements (compare column titled “Specific land use”).

Table 4-6: Land use, yield and production of corn (maize), wheat and selected other carbohydrate crops. Western Europe averages for 2002 (FAO, 2003).

	Area Harv	Crop yield	Crop prod	Starch content[2), 3)]	Specific land use
	1000 ha	t/(ha*a)	1000 t/a	t starch/t crop	(ha*a)/t starch
Corn (maize)[1)]	4,470	9.1	40,824	0.6	0.18
Wheat	18,158	5.8	105,659	0.6	0.28
Potato	1,318	36.0	47,399	0.2	0.15
Sugar beet[4)]	1,921	61.0	117,126		
Soy bean	244	3.3	795		

[1)] Maize and wheat: dried to less than 14% moisture; others: fresh matter

[2)] For corn, wheat: Venturi and Venturi (2003)

[3)] For potato: Wuerdinger et al. (2002)

[4)] 16% sugar.

Only very few of the LCA studies that have been prepared for bio-based polymers over the past few years address the aspect of land use. As a recent study prepared by Dornburg et al. (2003) shows, disregard of land use can lead to false policy conclusions. The reason is that **relating energy savings and GHG emission reduction of bio-based polymers to a unit of agricultural land instead of a unit of polymer produced, leads to a different ranking of options**. If land use is chosen as the basis of comparison, natural fiber composites and thermoplastic starch score better than *bioenergy production from energy crops*, while polylactides score comparably well and polyhydroxyalkaonates score worse. Additionally, including the use of agricultural residues for energy purposes improves the performance of bio-based polymers significantly. Moreover, it is very likely that higher production efficiencies will be achieved for bio-based polymers in the medium term. Bio-based polymers thus offer interesting opportunities to reduce the utilization of non-renewable energy and to contribute to greenhouse gas mitigation in view of potentially scarce land resources. While bioenergy has been actively addressed by policy for many years bio-based materials, some of which are more attractive in terms of efficient land use, have been given much less attention by policy makers. This is reasonable given the modest total land use required by bio-based polymers in comparison to other land uses. However should the "HIGH GROWTH" scenario eventuate, the observation that *per unit of agricultural land*, some bio-based polymers yield greater energy savings and GHG emission reductions than if the land were used to generate bioenergy should be duly considered by policy-makers.

It seems useful to deliberate about the **underlying reason for the potentially higher land use efficiency of bio-based polymers**: As explained by Dornburg et al. (2003) energy savings of bioenergy production are limited by crop yields. For a high yield crop like miscanthus, average yields in Central Europe are about 270 GJ/(ha*yr). In an ideal situation, biomass can thus substitute for fossil fuel on a 1:1 basis[35], which leads to energy savings of about 270 GJ/(ha*yr). On the other hand, the energy savings related to bio-based polymers can exceed this value since the energy requirements (i.e. feedstock and process energy) for petrochemical polymers can be much higher than for the corresponding bio-based polymers.

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[35] Even slightly higher substitution rates are possible if biomass is used as solid fuel in a more efficient energy conversion process than the reference

4.3 Results of the environmental assessment of the large-scale production of bio-based polymers

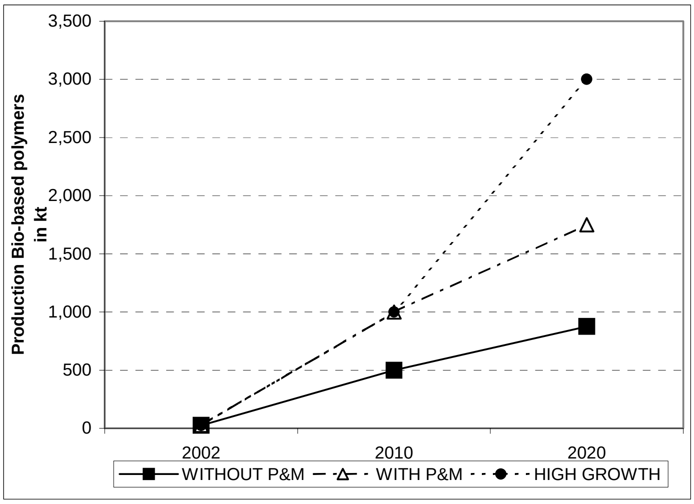
This chapter presents the results of the environmental analysis for the large-scale production of bio-based polymers in Europe for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH. The results are summarized in Table 4-7. The outcome for energy savings and GHG emission reduction is discussed in Section 4.3.1, while Section 4.3.2 deals with various aspects of land use (Figure 4-2 to 4-4 and Table 4-7).

Table 4-7: Summary of the results on the large-scale production of bio-based polymers in Europe for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH

	WITHOUT P&M	WITH P&M	HIGH GROWTH	*For comparison*	
Production Bio-based polymers, kt					
2002	25	25	25		
2010	500	1,000	1,000	*500/1000 1)*	*ECCP, 2001*
2020	875	1,750	3,000		
Additional land use, 1000 ha					
2002	3	3	3		
2010	63	125	125		
2020	113	225	975		
Energy savings, PJ					
2002	1	1	1		
2010	25	50	50		
2020	44	88	119		
GHG emission reduction, million t CO_2 eq.					
2002	0.1	0.1	0.1		
2010	1.8	3.5	3.5	*2.0/4.0 1)*	*ECCP, 2001*
2020	3.0	6.0	8.5		
Specific energy savings, GJ/(ha*a)					
2002	296	296	296		
2010	400	400	400		
2020	389	389	122		
Specific GHG em. red., t CO_2eq/(ha*a)					
2002	17.2	17.2	17.2		
2010	28.0	28.0	28.0		
2020	26.7	26.7	8.7		

1) Without and with Policies and Measures (P&M) respectively.

Figure 4-2: Production volumes of bio-based polymers for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH



4.3.1 Energy savings and GHG emission reduction by bio-based polymers

As Figure 4-3 shows the potential energy savings by 2010 due to bio-based polymers ranges between 25 and 50 PJ depending on the extent to which P&Ms are implemented. By 2020, 44 to 119 PJ could be saved. Relative to the total energy consumption by the EU chemical industry in 2000[36] these savings are equivalent to (Table 4-8):

- **0.5% without P&Ms by 2010**
- **1.0% with P&Ms by 2010** and
- **0.8-2.1% by 2020** (range covers all three scenarios).

Compared to the total primary energy consumption by the *total* economy (total EU)[37] the energy savings mentioned are equivalent to

- **0.04-0.08% by 2010** and
- **0.07-0.19% by 2020** (range covers all three scenarios).

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[36] Energy consumption by the EU chemical industry in primary energy terms (including feedstocks) amounted to 5600 PJ in 2000 (IEA, 2003).

[37] Total primary energy consumption by the EU amounted to 61400 PJ in 2000 (IEA, 2003).

Also from Figure 4-3, the potential GHG emission reductions by 2010 due to bio-based polymers range between 1.8 and 3.5 million t CO_2 eq. depending on the extent to which P&Ms are implemented and by 2020, 3.0 to 8.5 million t CO_2 eq. could be saved. Relative to the total CO_2 emissions from the EU chemical industry in 2000[38] these savings are equivalent to:

- **1.0% without P&Ms by 2010**
- **2.0% with P&Ms by 2010** and
- **1.7-4.8% by 2020** (range covers all three scenarios)**.**

Compared to the GHG emissions from the *total* economy (total EU)[39] the GHG emission reductions mentioned are equivalent to

- **0.04-0.08% by 2010** and
- **0.07- 0.20% by 2020** (range covers all three scenarios).

The order of magnitude of the results is confirmed by the estimates for 2010 that were prepared under the European Climate Change Programme (ECCP, 2001). The totals according to the ECCP study are about a factor 2 larger since also other important bio-based materials were taken into account, i.e. lubricants, solvents and surfactants. Limiting the comparison to polymers only, the ECCP still results in somewhat higher savings (as shown in Table 4-7: 2.0-4.0 Mt CO_2 eq. savings compared to 1.8-3.5 Mt CO_2 eq.; all data for 2010). While this comparison solely seems to confirm earlier insights, there is a rather **fundamental difference** between the two studies:

- In the ECCP study it was argued that, as a consequence of the scope of the study, practically only starch polymers were considered within the materials category 'polymers' (Patel, Bartle et al., 2002/2003) and that no other bio-based polymers (e.g., polylactides) were assumed to be produced in larger quantities. This approach was taken in order to avoid overestimation of the potential for emission reduction. At the same time, this approach implies that the ***real*** emission reduction potentials may be substantially larger.
- In contrast, this study (PRO-BIP) attempts to make realistic projections covering ***all*** bio-based polymers. Even though "conventional bio-based polymers", especially cellulosic polymers, have not been taken into account and the potentials related to PTT, PBT, PBS, PHA, PUR and PA were only roughly estimated, we believe that all major bio-based polymers have been accounted for in this study.

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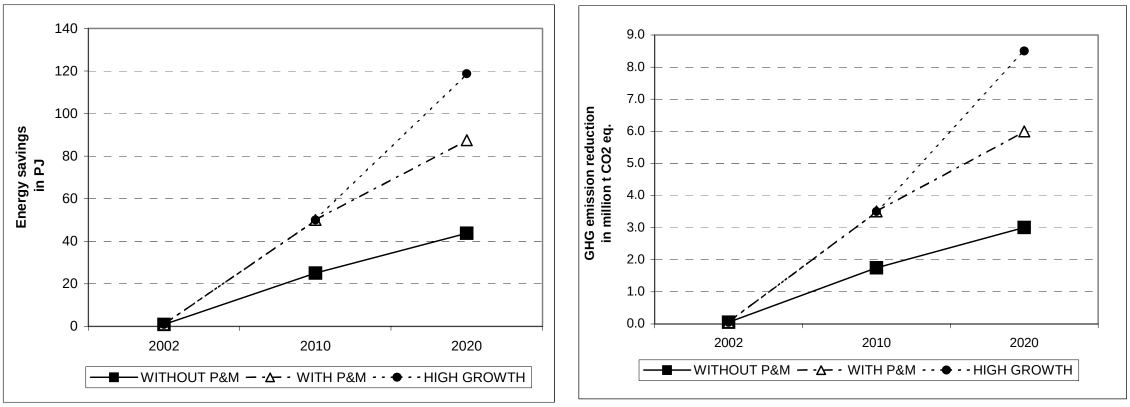
[38] CO_2 emissions from the EU chemical industry amounted to 175 Mt CO_2 in 1998 (CEFIC, 2001); Scaling with CEFIC index CO2 emissions 2000 vs 1998, one obtains 177 Mt (CEFIC, 2002). This figure includes only CO_2 emissions from energy use, i.e. from the production of process heat, steam and electricity; CO_2 emissions from non-energy use are excluded.

39 Total GHG emissions from the total EU economy amounted to 4112 Mt CO2eq. in 1998 (Gugele and Ritter, 2001). Scaling with CEFIC index CO2 emissions 2000 vs 1998, obtain 4165**.**

The different views of the two studies basically boil down to different expectations about the growth potentials for starch polymers. In this study, an attempt was made to substantiate the potentials by distinguishing between starch-based fillers for tyres and "classical" application areas. Clearly higher growth prospects might seem realistic if other, novel application areas have been overlooked or if the estimates for the application areas covered could be proven to be too conservative. Further information from the producers would be required to clarify these points. Depending on the outcome the calculations of this study would need to be revised.

Figure 4-3: Energy savings and GHG emission reduction for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH



If bio-based polymers develop successfully the reduced environmental benefits discussed above should be viewed as an important contribution of the chemical industry to sustainable development. At the same time the **production of petrochemical polymers is also expected to grow substantially** over the next two decades. This leads to one of the key questions posed at the outset of this study, i.e. whether the avoidance of environmental impacts enabled by the wide-scale production of bio-based polymers can (over-)compensate the negative environmental impacts caused by further growth of petrochemical plastics.

The upper part of Table 4-8 shows a simple calculation for petrochemical polymers. The projected production volumes have been taken from the so-called Base Case of the Clean Technologies project (Phylipsen et al., 2002). According to this study petrochemical polymer production in Western Europe is expected to increase by about 55% or 2.2% p.a. between the years 2000 and 2020 (for comparison: between 1980 and 2000, polymer production increased from 20.7 to 44.9 million tonnes, i.e. by 3.9% p.a). In line with the calculations for bio-based polymers the cradle-to-grave CO_2 emissions reported in Table 4-8 for petrochemical polymers do not account for possible credits related to energy recovery.These cradle-to-grave CO_2 emissions for petrochemical polymers have been estimated to increase from 220 million tonnes in 2000 to 350 million tonnes by 2020, i.e. by 130 million tonnes. This is **15 to more than 40 times more** than the emissions saved by bio-based polymers in the three secnarios WITHOUT P&M, WITH P&M and HIGH GROWTH (see last row of Table 4-8; reciprocal of this number gives the factor by which emission increases due to petrochemical polymers exceed emission reductions due to bio-based polymers). **This definitively shows that the lower specific environmental impact of bio-based polymers will not be able to (over-)compensate the additional environmental impacts caused by expected high growth of petrochemical plastics.**

Table 4-8: Emission projections for petrochemical polymers and of bio-based polymers in perspective

		2000	2002	2010	2020
Petro-chemical polymers	Production, Mt	44.9	47.3	57.4	70
	Cradle-to-Factory Gate energy[1], PJ	4000	4200	5100	6200
	Relative to 2000 EU chemical industry primary energy consumption of 5600 PJ[2] *(2000=100%)*	71%	75%	91%	111%
	Relative to 2000 EU total primary energy consumption of 61400 PJ[3] *(2000=100%)*	6.8%	7.1%	8.6%	10.5%
	Energy consumption increase for petrochemical polymers compared to year 2000, PJ	-	200	900	1100
	Cradle-to-Grave CO_2 emissions[4], Mt CO_2	220	240	290	350
	Relative to 2000 EU chemical industry CO_2 emissions of 177 Mt[5] *(2000=100%)*	124%	136%	164%	198%
	Relative to 2000 EU total emissions of 4165 Mt[6] *(2000=100%)*	5.3%	5.8%	7.0%	8.4%
	CO_2 emission increase for petrochemical polymers compared to year 2000, Mt CO_2	-	20	70	130
Bio-based polymers	Production, Mt	-	0.025	0.5/1.0/1.0	0.88/1.75/3.0
	Energy reduction due to bio-based polymers (w/o P&M, w.P&M, HG), compared to year 2000, PJ	-	0.9	25/50/50	44/88/119
	Relative to 2000 EU chemical industry primary energy consumption of 5600 PJ[2] *(2000=100%)*	-	0.02%	0.5/1.0/1.0%	0.8/1.6/2.1%
	Relative to 2000 EU total primary energy consumption of 61400 PJ[3] *(2000=100%)*	-	0.00%	0.04/0.08/0.08%	0.07/0.14/0.19%
	CO_2 emission reduction due to bio-based polymers (w/o P&M, with P&M, High Growth), compared to year 2000, Mt CO_2	-	0.1	1.8/3.5/3.5	3.0/6.0/8.5
	Relative to 2000 EU chemical industry CO_2 emissions of 177 Mt[5] *(2000=100%)*	-	0.06%	1.0/2.0/2.0%	1.7/3.4/4.8%
	Relative to 2000 EU total emissions of 4165 Mt[6] *(2000=100%)*	-	0.00%	0.04/0.08/0.08%	0.07/0.14/0.20%
Compen-satory effect of BBPs[7]	Energy reduction for bio-based polymers compared to energy increase for petrochemical polymers, base year 2000	-	0.5%	2.8/5.6/5.6%	4.0/8.0/10.8%
	CO_2 emission reduction for bio-based polymers compared to energy increase for petrochemical polymers, base year 2000	-	0.5%	2.6/5.0/5.0%	2.3/4.6/6.5%

[1] Calculated with a weighted overall value of 88 GJ/t polymer

[2] EU chemical industry energy use including feedstocks: 5600 PJ in 2000 (IEA, 2003).

[3] EU total energy use (all countries, entire economy): 61400 PJ in 2000 (IEA, 2003).

[4] Calculated with a weighted overall value of 5 t CO_2/t polymer

[5] EU chemical industry emissions: 175 Mt CO_2 in 1998 (CEFIC, 2001); scaled to figure for 2000 of 177 Mt.

[6] EU total emissions (all countries, entire economy): 4165 Mt CO2 in 2000.

[7] 100% = Full compensation (reduction due to bio-based polymers equal to increase due to petrochemical polymers)

At the beginning of Section 4.4 and when explaining the input data used (Table 4-1 and Table 4-5) it was pointed out that a few simplifying assumptions are made which could result in overestimation of the energy and CO_2 savings. This potential overestimation is not of concern in view of the relatively low contribution of bio-based polymers to emission reduction at the **national** level and overcompensation by additional emissions caused by the continued growth of the petrochemical polymers. In other words, lower values for the input data could not change the overall picture of this analysis.

4.3.2 Land use requirements related to bio-based polymers

As described in Section 4.2 the land use requirements assumed for the product category “Other bio-based polyesters, PUR and PA”. These materials have been assumed to emerge only in the HIGH GROWTH scenario. This explains why the land use for this scenario is five to ten times higher than for the scenarios WITHOUT P&M and WITH P&M (see Figure 4-4). This feature is also apparent in the specific indicators shown in Figure 4-5.

Figure 4-4: Additional land use related to the production of bio-based polymers for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH

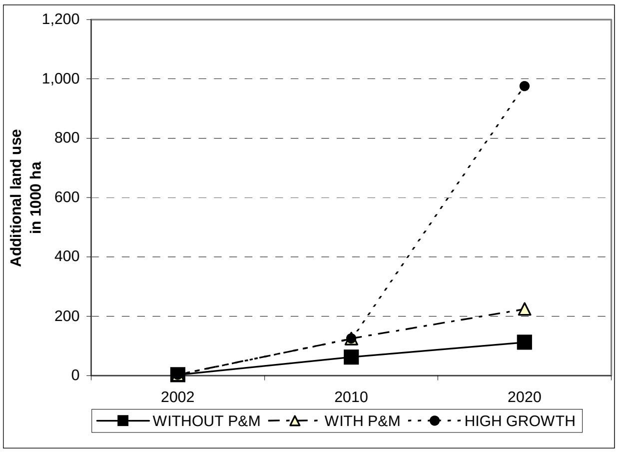
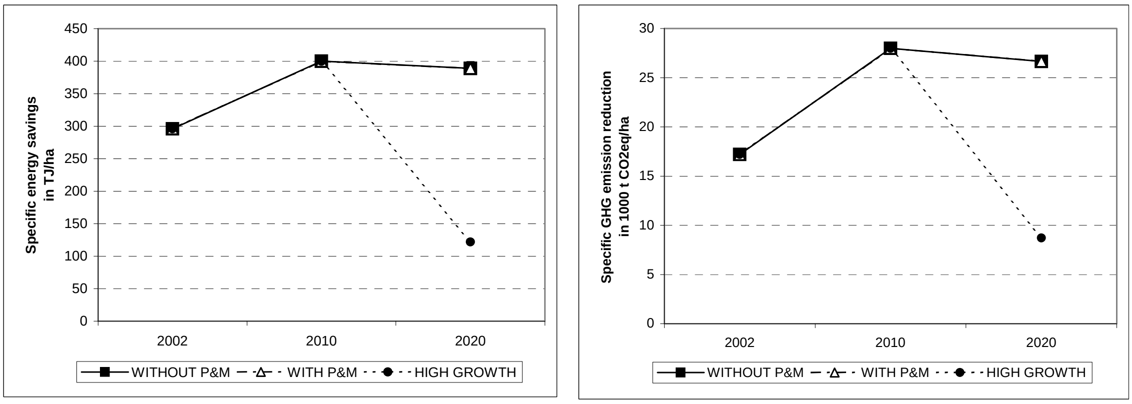


Figure 4-5: Specific energy savings and specific GHG emission reduction (in both cases per unit of land used) for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH



As discussed at the end of Section 4.2.2 the maximum specific energy savings related to bioenergy production lie in the range of 270 GJ/(ha*yr) or 0.27 TJ/(ha*yr). According to Figure 4-5 this is less than the savings that are achievable in the scenarios WITHOUT P&M and WITH P&M. The production of bio-based polymers with larger land requirements in the HIGH GROWTH scenario (compare also Table 4-5) causes the overall specific energy savings to fall below the 0.15 TJ/ha mark by 2020 (Figure 4-5).

This should be avoided and 'land-efficient' forms of bioenergy should be implemented instead.

The additional land use in thousands of hectares per annum (see Figure 4-4 or Table 4-3) can be put into perspective by comparing it with total land use in EU15 for various purposes. Table 4-4 shows additional land use as a proportion of the total land use in EU15 for wheat (2002) (FAO, 2003), cereals (1997), set-aside land (1997) and industrial crops (1997) (Eurostat, 2003).[40] If all bio-based polymers were to be produced from wheat, just over 1% of the land would be required for the case WITH P&M; up to a maximum of 5% for the HIGH GROWTH scenario. As a proportion of total cereals these figures are a factor 2 lower. **This means that bio-based polymers will not cause any strain within the EU on agricultural land requirements in the near future.** Compared to total set-aside land (1997 values), the percentage of land required is 3.6% WITH P&M and 15.4% for HIGH GROWTH; requirements as a proportion of total industrial crops (1997) are similar to those for set-aside land[41]. **Land use requirements for bio-based polymers are thus seen to be quite modest. There could, however be some conflict of interest with bioenergy crops for utilisation of set aside or industrial crop land after 2010 with the HIGH GROWTH scenario.**

Table 4-9: Additional land use for bio-based polymers as a proportion of other land uses in EU-15 for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH

	WITHOUT P&M	WITH P&M	HIGH GROWTH	For comparison	
Additional land use, 1000 ha					
2002	3	3	3		
2010	63	125	125		
2020	113	225	975		
Additional land use as % of total for wheat (EU15, 2002) *)					
2002	0.0	0.0	0.0	*18.16 million ha*	*wheat*
2010	0.3	0.7	0.7		
2020	0.6	1.2	5.4		
Additional land use as % of total cereals (EU15,1997)					
2002	0.0	0.0	0.0	*38.96 million ha*	*cereals*
2010	0.2	0.3	0.3		
2020	0.3	0.6	2.5		
Additional land use as % of total set-aside land (EU15, 1997)					
2002	0.0	0.0	0.0	*6.33 million ha*	*total set-aside*
2010	1.0	2.0	2.0		
2020	1.8	3.6	15.4		
Additional land use as % of total industrial crops (EU15, 1997)					
2002	0.0	0.0	0.0	*6.55 million ha*	*total ind. crops*
2010	1.0	1.9	1.9		
2020	1.7	3.4	14.9		

*) Wheat: Eurostat (2003); Other data: FAO (2003)

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[40] Assume these figures for land use land use will not change between 2000 and 2020. While this is a gross assumption it is considered adequate for the rough estimate required here.

[41] This proportion is probably already significantly lower in 2003 terms since according to EC DG XII (1994) the amount of set-aside land in the EU should increase substantially up to 25%, equivalent to about 30 million ha (Metabolix, 2003).

4.4 Socio-economic effects of the large-scale production of bio-based polymers

Apart from environmental benefits the production of bio-based polymers is also expected to have positive socio-economic effects, particularly in relation to employment in the agricultural sector (employment in the chemical industry is expected to be comparable to petrochemical polymers, therefore resulting in no net additional employment). If the assumption is made that agricultural land will be utilised that would otherwise be set aside or used in a less productive manner, then the production of bio-based polymers leads to increased employment in the cultivation and harvesting of starch and sugar crops. Estimations for additional employment (expressed in full-time equivalents, FTE) are given in Table 4-5. These figures were calculated using labour requirements for the production of corn and wheat in the Netherlands and Germany (averaged figures: 8.5 h/(ha*a) until 2005, thereafter 11 h/(ha*a), together with volume projections already discussed in section 4.3. Employment effects are seen to be very modest - employment generated by bio-based polymers in 2010 is projected to be about 0.005-0.01 percent of the current EU employment in the agricultural sector. In 2020, in the HIGH GROWTH scenario, about 0.08 percent are employed. These low values may seem obvious in view of the rather low per capita production discussed earlier (Table 3-3).

Table 4-10: Additonal employment in the agricultural sector for the three scenarios WITHOUT P&M, WITH P&M and HIGH GROWTH

	Additional employment (FTEs) 1), 2)			*For comparison: Total agricultural sector, 2002 3)*
	WITHOUT P&M	WITH P&M	HIGH GROWTH	
2002	16	16	16	*Germany 917,000*
2010	260	510	510	*EU-15 excluding NL, FR:*
2020	460	920	3,980	*5,081,000*

1) Data from PAV (2000) and Wintzer et al. (1993).

2) 1 FTE = 2080 hours.

3) LABORSTA (2003); assumption 1 unit employment = 1 FTE according to ER (2000): avg worked hours in agriculture, 1996 = 40.3 h

4.5 Production value and potential leverage of fiscal measures/subsidies

4.5.1 Production value

A first estimate of the production value of the bio-based industry can be made by estimating its turnover, i.e. by multiplying its production with the sales price of the merchandise. Obviously the two parameters are related, with higher production volumes being coupled with relatively low prices. In the extreme case, bio-based polymers would reach similar price levels as their petrochemical counterparts. An assumed price range of 1-2 EUR/kg bio-based polymer translates to a **maximum production volume of roughly 1-2 billion EUR by 2010 (scenarios WITH P&M and HIGH GROWTH) and 3-6 billion EUR by 2020 (scenario HIGH GROWTH).**

4.5.2 Subsidies, fiscal measures and tax reduction

As discussed in Section 4.2.2, bio-based polymers offer the potential of saving energy and reducing GHG emissions with lower land requirements than bioenergy. This may lead to the conclusion that bio-based polymers should be eligible for similar supportive policy measures as bioenergy. These could, for example, be analogues (or equivalents) of green certificates or of feed-in tariffs that are both applied for the promotion of renewable electricity. Theoretically, the inclusion of bio-based materials in the EU Emission Trading Scheme (EU ETS) would be another option. The latter can be expected to be relatively unattractive for the bio-based industry, due to the comparatively low value of the so-called emission allowances. For this reason this chapter discusses only the financial implications of a linkage between bio-based polymers on the one hand and feed-in tariffs or Green Certificates on the other.

Vries de et al. (2003) have compiled **feed-in tariffs** for green electricity in all European countries. Outliers excluded, most values for the various forms of bioenergy fall in the range of 5 to 7.5 ct/kWh. Bioenergy was chosen as basis for comparison since biomass is used as a resource also in the case of bio-based polymers. Other forms of green electricity differ not only with regard to the resource base but also concerning cost (e.g., photovoltaics is much more expensive) and are therefore not comparable. Based on information provided for Austria on base prices we estimate the price level of conventional electricity to be around 2.5 ct/kWh (2-3 /kWh). This means that the **net financial support of producers of green electricity is around 2.5-5 ct/kWh.**

Similar values are reported by Uyterlinde et al. (2003) who estimated the certificate price for the case that an EU market for tradable **Green Certificates** emerges. The authors point out that the equilibrium price directly depends on the level of the demand created in this market, in other words on the ambition level of policies. Assuming that the quotas are based on the EU targets for 2010, the prices of Green Certificates are expected to be in the range of **5-6 ct/kWh**. This price is additional to an average electricity commodity price of 3 ct/kWh in the baseline scenario. In the period beyond 2010, the level of the Green Certificate price is directly dependent on whether new targets are agreed in the EU. For the case that the ambition level does not further increase and targets only see a moderate increase in absolute terms as a result of the growth in electricity demand, Uyterlinde et al. (2003) expect the Green Certificate price to stabilise at a lower level of **3-4 ct/kWh**.

Combining the two sources, the net support of green electricity producers is in the range of **2.5-6 ct/kWh**, with the higher end being representative for the period until 2010 and the lower end serving as estimate for the period beyond 2010. Assuming an average efficiency for power generation of 33% in the EU, this translates to a **net support of 2.3-5.55 EUR per GJ of primary energy**.[42] As shown in Table 4-1 the (primary) energy savings for average to very attractive cases amount to 25-50 GJ/tonne of bio-based polymer. Combining these two pieces of information yields

- for the **period 2000-2010** (calculated with 6 ct/kWh or 5.55 EUR per GJ of primary energy) a maximum range of 0.14-0.28 EUR/kg bio-based polymer, with an **optimistic value lying at ca. 0.2 EUR/kg bio-based polymer** (valid for savings of 35-40 GJ/tonne of bio-based polymer)[43]
- for the **period 2010-2020** (calculated with 2.5 ct/kWh or 2.3 EUR per GJ of primary energy) a maximum range of 0.06-0.12 EUR/kg bio-based polymer, with an **optimistic value lying at ca. 0.1 EUR/kg bio-based polymer** (valid for ca. 40 GJ/tonne of bio-based polymer).

These values (0.1-0.2 EUR/kg bio-based polymer) can also be interpreted as the **willingness to pay** of society for the environmental benefits of a bio-based polymer with a good to outstanding environmental performance. A financial support of this level (0.2 EUR/kg until 2010) would represent a maximum of 10% of the current selling price of bio-based polymers (e.g. about 2.2–3.0 EUR/kg for PLA and most starch polymer grades). This leads to the following considerations:

- In the first instance, this result may be surprisingly low in view of the outstandingly attractive position of some bio-based polymers (including some starch polymers) compared to bioenergy with regard to land use. While land use efficiency and the cost of production obviously represent different dimensions, a higher equivalent financial support for bio-based polymers could possibly have been expected. The main reason why this is not the case is the difference in scale and maturity of production. While bioenergy can be produced with rather mature technology at comparatively low price, this is not (yet) the case for bio-based polymers.
- On the other hand Table 4-11 shows the consequences for a hypothetical SME producing bio-based polymers. One may conclude that a financial support of 0.2 EUR/kg can indeed decisively increase the resources that are available at the company level for conducting R&D and improving the competitiveness in many other ways.

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[42] The calculation made is presented at the example of the higher value of 6 ct/kWh:
$6\ \text{ct/kWh} * 1\ \text{kWh}/3.6\ \text{MJ}_{el} * 1000\ \text{MJ}_{el}/\text{GJ}_{el} * 1\ \text{GJ}_{el}/ 3\ \text{GJ}_{primary} * 1\ \text{EUR}/100\ \text{ct}$
$= 5.55\ \text{EUR/GJ}_{primary}$

[43] The calculation for this case is:
40 GJprimary/tonne bio-based polymer * 5.55 EUR/GJprimaryG
= 222 EUR/tonne bio-based polymer = ca. 0.2 EUR/kg bio-based polymer

Table 4-11: Possible effects of a financial support of bio-based polymers for a hypothetical producer (SME)

	Production kt	Specific monetary flows EUR/kg	Absolute monetary flows milllion EURO
Financial support	25	0.2 (P&M)	5.00
Turnover	25	3.0 (price)	75.00
Value added*)			45.00*)

*) Rough estimate based on the assumption that about 40% of the total production cost are caused by purchases of raw materials

It can be concluded that **the society's willingness to pay for green electricity** (from biomass) **can translate into a level of financial support that would help to improve the competitiveness of bio-based polymers**. This seems to be the case for the short term and possibly even more so for the longer term: If production costs decrease substantially then a financial support of 0.1-0.2 EUR/kg bio-based polymer could possibly contribute in an even more meaningful way to accelerated diffusion. However, it would then also remain to be seen whether society would be equally willing to pay for green polymers as for green electricity (results of the Kassel Project indicate that this could be the case; IBAW, 2003; Lichtl, 2003). Moreover, verification of the savings realised is more easily possible in the case of power generation (with commercialised technology) than for a complex chemical plant with its numerous flows, the changes that may be made to the process and/or to the product and the confidentiality that may represent an obstacle to verfication. Differences in energy savings by types of bio-based polymers would possibly also need to be taken into account. In economic terms, this means that the **transaction costs** are probably relatively high for implementing an equivalent of feed-in tariffs or of Green Certificates for bio-based polymers.

The latter disadvantages are not present in other forms of financial support, such as a **reduction of VAT rates**. Full exemption from VAT (16-20% for most of the EU countries; spread 15-25%) would, however, represent a much larger financial support of bio-based polymers than the equivalent values derived above from green electricity and could therefore not be justified on a large scale. Exceptions could be certain products with additional indirect financial or other benefits (e.g. biodegradable bags in waste management); here, full VAT exemption could be justified. For all other products, a **reduced VAT rate** would be an option, e.g. a **tax deduction by 4%** as has been proposed by the working group "Renewable Raw Materials" (RRM) as part of its work under the European Climate Programme. For current bio-based polymer prices of 2.2–3.0 EUR/kg, the resulting savings for the consumer are around **0.1 EUR/kg bio-based polymer**, i.e. on the lower side of the range derived above from the support granted to green electricity (0.2 EUR/kg until 2010 for a bio-based polymer saving 35-40 GJ/tonne). This lower value could be justified by the fact that the transaction costs related to verification and monitoring are avoided; the tradeoff is lower specificity of a (generally defined) reduction in VAT rates.

5. Discussion and Conclusions

In this chapter, limitations to the report are identified, the findings of Chapters 2 to 4 are revisited and discussed, and the ground prepared for the discussion in Chapter 6 of possible EU policy instruments.

5.1 An emerging sector

Technology developments and markets

As seen from the in-depth look at technologies in Chapter 2, bio-based polymers is an **emerging field** that is characterised by a number of different developments as shown in Figure 5-1. One development is that **established chemical companies** are moving into **biotechnology** and engaging in R&D efforts: examples include BASF, Cargill, Degussa, Dow, DSM, DuPont and Uniqema. Since such companies may not have enough in-house expertise to make the transition to biotechnology on their own, they may choose to set up **new collaborations** with **biotechnology companies**. Apart from having a knowledge base in the life sciences, biotech companies are typically able to work in a more flexible and innovative manner, engage more in high tech and can accept a higher risk. Main drivers are the biodegradability of the product, the reduction in production costs associated with using carbohydrate feedstocks due to advances in fermentation and aerobic bioprocesses, unique properties of bio-based polymers and (to a lesser extent) the use of renewable resources. As an example of such a collaboration, DuPont and Genencor have developed a high yield bioprocess for 1,3-propanediol (PDO) from glucose. DuPont plans to utilise this PDO in the production of the polyester poly(trimethylene terephthalate) (PTT) in the near future. Another example is the partnership between **consumer goods producer** Procter &Gamble (P&G) and Kaneka, in which Kaneka holds the composition of matter patent to a type of PHA polymer and is developing the production process in Japan, while P&G holds the processing and application patents and is developing the product slate. While such collaboration is nothing new in itself, it presents a particular challenge to the plastics manufacturer, who is traditionally closely tied to the ‘materials and methods’ of the petrochemical industry.

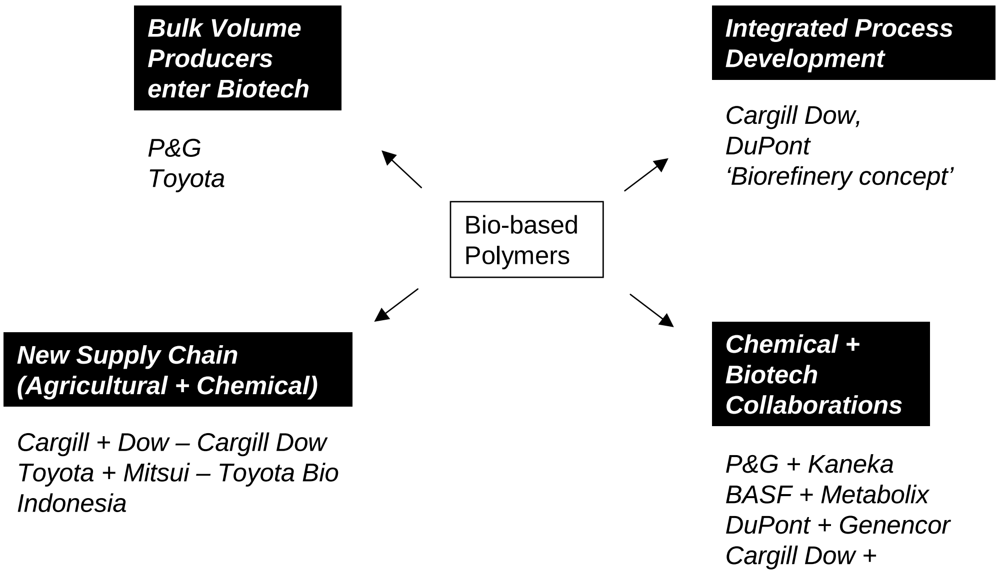
In contrast to the approach taken by fine chemicals and pharmaceuticals producers, companies interested in harnessing biotech for bulk volume markets are adopting a different approach in the pursuit of profitability targets, an important element of which is **integrated process development**. In this approach, rather than focusing primarily on optimisation of the fermentation step, the entire production chain from preprocessing through fermentation to product workup is scrutinised in an attempt to optimise the whole so as to meet a number of targets including simplified and more cost-effective fermentation media, higher productivity (from the entire process train), improved robustness of microorganisms (extended lifetime, more tolerant to processing conditions) and reduction in quantity and/or potential environmental impact of liquid and solid waste streams. Two companies solidly pursuing this approach are Cargill Dow and DuPont, both of which have received considerable funding from US agencies within the context of the development of biorefineries with corn (maize) as the primary feedstock.

In the biorefinery concept, a highly integrated facility utilises a bulk-volume renewable resource feedstock to produce a slate of products ranging from low price commodity chemicals to higher price and lower volume specialty chemicals. Analogous to the petrochemical refinery, the biorefinery starts up producing one or a few principal products and evolves with time and technology development to add value to what may otherwise be considered waste products. Thus the Cargill Dow production facility could equally be considered as a biorefinery in an early stage of development where the product with the highest added value, in this case polylactic acid, is the first to be produced and marketed, to be followed at a later stage by other lactic acid derivatives such as esters (e.g. ethyl-, n-butyl-, isopropyl lactate, used as biodegradable solvents and cleaning agents) and lactic acid salts (e.g. sodium-, potassium- and calcium lactate, used mainly in the processed foood industry). Also as the plant develops, corn biomass (e.g. stalks and husks), typically a waste product, will be increasingly utilised for on-site energy generation and as a process feedstock via hydrolysis of lignocellulosics.

Another development is that polymer manufacturers are setting up joint ventures with **agricultural companies** to guarantee cost, quality and consistent supply of raw material (primarily, carbohydrate crops). This may be seen as a value chain analogous to that of the oil winning plant, the petrochemical refinery, and the plastics manufacturer and is best represented by Cargill Dow’s value chain from corn wet milling (offsite) through lactic acid fermentation to polylactic acid production
One notabledifference between these two value chains is that while the supply (and thus the price) of oil may be subject to political conflicts and/or scarcity, industrial crops can be grown within the national boundaries and are generally viewed as a politically secure supply option. New uncertainties, however, are introduced due to the effects on crops of weather, disease and pests. Crops are also not as easily stored as petroleum.

Another important impact of the new value chain is that while petrochemical complexes are ideally located close to the oil supply (typically, a port) large-scale bio-based polymer plants are most economically placed in an agricultural region. In the longer term, this could be expected to lead to a diversification of the industrial base and an increase in infrastructure in agricultural areas while reducing the intensity of industry in the vicinty of (overcrowded) ports/coastal areas where petrochemical refineries and associated chemical plants are typically sited.

Figure 5-1: Synergies and collaborations in the emerging bio-based polymer industry



The bio-based polymer industry is thus characterised by **new synergies and collaborations**, with strong links to biotechnology, with **nanotechnology** (e.g. addition of nanoparticle clay to PLA for improved thermal properties; starch polymer fillers for tyres) starting to play a role. Higher value-added products within the main market sectors are being targeted; e.g. Sony PLA Walkman™, starch-blend foils for food packaging. This view of development is also supported by todays' major producers, who more or less uniformly state that innovation must play an important role alongside substitution in gaining market share for bio-based polymers. As an example, P&G is developing applications for PHA polymers both to fill material performance gaps and to meet the demand for biodegradable short-life products (e.g. nappy backing material).

Today, numerous activities related to bio-based polymers are under way involving both small to medium enterprises (SME) and large scale chemical companies in **Europe (EU-15), the US, and Japan**, with some participation from Australia, Latin America and other Asian countries. **Technology push** features strongly in the activities of all major players. Innovative products are now on the market in the **packaging, electrical & electronics, and agricultural sectors** (see Table 2-35), and according to P&G (2003), numerous requests and ideas for new products from bio-based polymers are submitted by customers each week. While we can be reasonably accurate in identifying the handful of current major bio-based polymer producers (including Cargill Dow, Novamont, Rodenburg, Biotec) and some companies quite clearly state their intentions to enter the market (Hycail, Toyota, P&G, DuPont); there are still a lot of unknown future players in the market, since companies are generally reluctant to disclose information at the pre-commercial stage. Shell, BP, and Bayer are among the major companies exploring (or in some cases revisiting) options for using bio-based feedstocks for the production of polymers and bulk chemicals. Aside from the detailed company plans presented in Chapter 2, a few companies have provided the authors of this report with confidential information concerning their plans for bio-based polymers; among these: one European company is preparing the construction of a bio-based polyester production facility in a tropical country; and a large-scale Japanese enterprise

is currently developing a strategy for the extension of their product portfolio towards bio-based polymers.
While the interest in bio-based polymers at the company level essentially boils down to a combination of new market opportunities and more sustainable solutions for established markets, **national or regional interests** served by bio-based polymers differ substantially at present: in the US, resource security and resource utilisation are paramount; in Japan, a recent strong drive towards products with a green image (e.g. Panasonic, Teijin and Toyota); in Europe, resource utilisation, GHG, and compostability). It is expected that by 2010 there will be a much greater alignment of national interests steering bio-based polymer development at the global scale; with environmental benefits and biodegradability coming to the fore, together with a stronger focus on renewable feedstocks. For Europe, other important issues will be land allocation, socio-economic effects (e.g. job-creation in agriculture); and the ongoing debate concerning genetically modified organisms.

Behaviour of actors and obstacles

While patents are often considered to determine the course of an industry's development, patents filed in the bio-based polymers sector do not seem to be perceived as an insurmountable obstacle. This may be attributed to two main reasons: in the first place, some of the basic technology was patented a long time ago and is therefore equally available to all current players. Secondly, there is no uniform strength and reliability of patents in the various world regions; for example, European producers consider U.S. patents to be relatively easily contestable in Europe. These two reasons explain why despite the fact that Cargill Dow has filed patents in Europe, Hycail, Inventa-Fischer, Snamprogetti and possibly further European actors are seriously working on implementation strategies for PLA.

Because the bio-based polymer industry is still in its infancy, there is a lack of experience with bio-based consumer goods. Products now emerging on the market (see Table 2-35) are thus in many cases the prototypes or pioneers. These products will play an important role in shaping public perception, which could fall either way. Taking the example of the fibres market: if the new bio-based fibres fail to meet these performance requirements within their target markets (e.g. sports clothing), this could prove to be a major setback to producers. If, on the other hand, bio-based fibres live up to expectations for e.g. moisture wicking, comfort and strength, these fibres may be expected to gain recognition as belonging to an 'own' category alongside petrochemical-based synthetic fibres, natural fibres and man-made cellulosics, and of sporting both the 'high-tech' label as well as the 'natural' label.

Further to the subject of consumer perception, Metzeler (2003) presents the argument (in relation to PUR) that the public is often under the false impression that such a bio-based material is less durable than the 100% petrochemical-derived equivalent. In the Kassel project it was found that on the one hand, consumers were interested in principle in purchasing a bio-based polymer product instead of a conventional polymer product. However, according to the experience of one producer, most consumers were not prepared to pay a higher price (even 5c higher) unless there were clearly perceived performance improvements associated with the new bio-based polymer product (Rodenburg, 2003). This is an example of one of the many hurdles that producers of bio-based polymers must successfully clear in order to reach economic viability. Another hurdle comes in the form of the polymer converter's resistance to the introduction of a new material. The existence of such hurdles can set back a company's plans to go bio-based, and lend weight to the notion that the government should actively support company efforts to develop and market bio-based polymers, rather than simply 'scheduling the transition'.

Apart from the innovators and leaders of the bio-based polymer world (i.e., those doing the 'pioneering and prototyping', the herd instinct (imitation of competitors) also seems to be at work. While this may be thought of as increasing the total momentum of bio-based polymer developments, it also entails substantial risks to the emerging sector. However, to a certain extent this is a feature of any technological innovation – whether ultimately successful or not.

Little study has been done concerning the desires and views of the interested and affected parties (e.g., consumers that will or do use products made of bio-based polymers). Among them, consumers' willingness to support the development of products because of their superior environmental performance or conservation of nonrenewable resources is a crucial element. However, consumer views are notoriously complex and it is not sufficient to assume that because there is a willingness to pay for one environmental good, this same support will accrue to bio-based polymers. This is hence an area that should be addressed in future analyses.

5.2 Limitations of the report

A number of limitations to this study may be identified, particularly in relation to the projections and to the environmental analysis.

Technology and product characterisation

In the first place, this study makes use of information obtained from personal communications with representatives of current and prospective producers of bio-based polymers. While these individuals are generally highly qualified in terms of their technical knowledge and knowledge of the market, it must be clearly stated that no strict cross-checking of the validity of information takes place, as opposed to literature published in refereed journals. In some cases, pointers are also taken from trade journals that are generally focused on industry needs and often make use of company press releases announcing company intention (to build at location Y or produce X thousand tonnes) rather than simply reporting annual production and tonnage sales. The literature in the field of bio-based polymers is often focused on materials engineering (e.g. for surgical implants) or microbiological engineering rather than process improvement and innovations in the bulk materials sector. For these reasons, a pragmatic approach has been taken, whereby the 'best available source' is quoted and any speculative elements stated as clearly as possible.

In the study, the polymers of interest have been identified and the most attention given to those with a foothold in the market. Five years ago, only starch-based polymers were considered as having prospects for bulk production; now PLA is the largest type in capacity terms, and in five years time it may well be other (partially) bio-based polyesters such as PTT exhibiting the strongest growth and thereby polarising the field of bio-based polymers into a set of 'inherently biodegradable' and one of 'hardly biodegradable' materials.

Two main frames of reference may be considered when determining criteria for the success of bio-based polymers. One is the company's ability to produce a material of consistent quality, to place this on the market at a competitive price and to develop the market in co-operation with polymer processors and their clients. The other is the ability of the material to meet all demands at both the bulk use stage (by the converter) and the end use stage (consumer) so that the material is viewed by the customer as being an appropriate substitute for the given application, or as an appropriate material for a novel application. For both of these, the substitution potential is an important reference point. This involves considering the full range of material properties for the bio-based polymer, and placing these alongside the property set of equivalent petrochemical polymers. Relative quantities for a given application need to be known, and relative prices. Other less tangible qualities will also affect the extent to which substitution takes place. As this field of knowledge is the domain of the polymer chemist, the materials scientist and to a certain extent the marketing specialist, in this study polymer properties are considered only cursorily and a weighting of 'low', 'medium' or 'high' substitution potential (by polymer type) is used to make a first estimate of the maximum possible substitution potential.

In determining the price competitiveness of each biopolymer, the economic optimum for each of the bio-based polymers at any point in time is most accurately determined based on a number of process specific parameters including the substrate-related yield, productivity, final (or steady-state) concentration of the product in the fermentation broth, and the % loss in the product recovery steps; which in turn are dependent on technological developments. Analysis at this level, while undoubtedly being more systematic and giving greater insight into specific processes (e.g. analysis of bottlenecks, data sensitivities), is beyond the scope of this study. Instead it was chosen to perform a meso level analysis for current and future price competitiveness by compiling growth data at the company level and projecting this at the industry and macro levels with the use of experience curves (Section 3.3).

Environmental assessment

While according to best practice the comparison of environmental impacts should be based on the full life cycle of the product, the range of materials and the large number of possible end products covered in this study render a product-by-product analysis infeasible. As such, it was chosen to take a functional unit of one kilogram of polymer in primary form (pellet/granule) for each polymer type or sub-type. A cradle-to-grave approach (excluding the use phase) has been chosen. Assuming energy neutral incineration (no net energy export) and assuming further that energy use for transportation in the waste management stage may be neglected, it follows that the total energy requirement of the system 'cradle-to-grave' is practically identical to that of the system 'cradle-to-factory-gate'; therefore the latter has been used. For greenhouse gas (GHG) emissions, the results for each of the two system boundaries cannot be equated due to the release of CO_2 from fossil carbon embodied in the polymers (some fossil carbon may be embodied in bio-based polymers and fossil carbon is definitely embodied in petrochemical polymers which serve as the basis for comparison). For this reason, the cradle-to-grave approach has been chosen for calculating GHG emissions.

For a more accurate analysis at the EU level, it would be necessary to know for all (major) end products the share of each of the polymers involved in their production, the weight, the transportation distances and modes and the mix of waste treatment technologies applied including their key characteristics. While this may be possible for a few end products, a simplified approach is unavoidable when calculating the impacts for an entire group of materials (here: polymers) in a country or a region. It could, however, be worthwhile to conduct several calculations for different types and combinations of waste management technologies.

A note of caution should accompany the simplified approach referred to above: Different biopolymers may have very different impacts in different localities at different times. As such, the results presented in this report are generalities that apply to the broad category of bio-based polymers. Since the body of current scientific knowledge regarding the environmental impact of bio-based polymers is still growing substantially, the relative uncertainty of reported impacts is still high.

The environmental impact categories covered in this study are energy use, GHG emissions and land use. Lack of data due to the early stage of technology development and variations in life cycle assessment methodologies found in published studies are among the reasons for choosing to focus on a limited number of impact categories. Other impact categories (e.g. human and environmental toxicity, water quality, soil fertility) are likely to be very significant for these materials, but cannot be assessed. Making general conclusions about the environmental desirability of bio-based polymers is thus not justified on the basis of this limited assessment. It is quite possible that inclusion of other impact categories might make biopolymers even more attractive from an environmental perspective, but this is not known with any certainty.

In terms of specific polymer types, the quality and availability of data for conducting environmental impact assessments varies considerably: for starch and PHA, several studies are available though each is limited to specific products (e.g. modified starch, P(3HB); for PLA one study has been published by Cargill Dow; and own estimates had to be made for the group of potentially bio-based polyesters (PTT, PBT, PBS).

In Section 5.1 some impacts associated with the new value chain for bio-based polymers were identified. Taking a broader view of this, it is clear that the transition from petroleum-based polymers to bio-based polymers and associated with this will bring to the fore many additional environmental impacts, some of which are not yet fully appreciated by society and the scientific community alike. Society will most likely evaluate the impacts of an industrial feedstock based system quite differently to that of a primarily food-based agricultural production system. An appraisal of these factors is beyond the scope of this study; additional research is required to address this. Again, these limitations necessarily limit the conclusions which may reasonably drawn by policy-makers and others based on the content of this report.

To summarise: while the quality and availability of data for conducting environmental impact assessments for the long term is not fully satisfying, in view of the final results the information basis may be considered sufficient for this type of study.

Influencing factors and projections

The study is by nature subject to major uncertainties, since a set of assumptions must be drawn up about how technologies and markets will develop between the present time and 2020. Expectations change from year to year with regard to both the extent and the direction of technological development; particularly in the field of molecular engineering of microorganisms. As an example, DuPont and Genencor have been successful in significantly improving productivity with a new bioprocess to 1,3-propanediol. On the other hand, failure of a key player (as experienced by Monsanto some years ago) could have a substantial negative effect on the ‘self-confidence’ of the emerging bio-based polymer industry and consequently slow down the dynamics. In this study, attempts have been made to account for such uncertainties related to influencing factors and projections by distinguishing between three scenarios: a base case without policies and measures (P&M), a case with P&M (the most likely case) and an optimistic high growth case. As stated in Section 3.0, while these scenarios should not be mistaken for forecasts, they are nevertheless of crucial importance in developing a strategy. We believe that these three scenarios adequately address the range of possible developments for the bio-based polymer industry up until the year 2020 and allow for a comprehensive analysis of the effects thereof.

To conclude, we believe that we have made, wherever necessary, appropriate choices to avoid false conclusions. Scenario analysis is applied to account for diverse future trajectories. However, as for every study concerning the future, a large degree of uncertainty cannot be avoided. The reader is therefore requested to keep in mind this limitation and is referred to the “Note of caution” at the beginning of this study.

5.3 Substitution potential and growth projections

In Chapters 2 and 3, estimates have been made firstly for the technical substitution potential and then for more realistic production scenarios that implicitly take into account price differentials and other influencing factors.

For the technical substitution potential, the material property set of each bio-based polymer was compared to that of each petrochemical-based polymer, a score given for the maximum percent substitution and these scores added up to give a total (Tables 2.31a and 2.31b). For EU-15, it is estimated that up to 14.7 million tonnes or 34% of the total current polymer production could be substituted with bio-based plastics. For the smaller synthetic fibres market, maximum substitution amounts to 700 thousand tonnes or 20% of EU-15 production. For total polymers (plastics plus fibres), the **maximum substitution potential of bio-based polymers** in place of petrochemical-based polymers is thus estimated at **15.4 million tonnes** (2002 terms), **or 33% of total polymers** (time independent). An important point concerns the apportioning of market share due to novel applications on the one hand and direct substitution on the other. This has been addressed by assuming as follows: at low volumes (i.e. the current situation), novel applications may represent a significant percentage of the total volume of bio-based polymers; but the higher the volume of bio-based polymers, the larger the amount of petrochemical polymers that are *directly substituted* by bio-based polymers.

Before attempting to make growth projections, an analysis of influencing factors along the value chain for the whole life cycle of bio-based polymers is called for. This is addressed in Chapter 3.1: main influencing factors are first identified in a mind map (Figure 3-1); these factors are then organized into stages in the value chain (Figure 3-2 and Section 3.1); and key influencing factors and their impeding or stimulating impacts further qualified in Table 3.1. What we see from this analysis is that there are a large number of economic, social, ecological and technological influencing factors relating to the bio-based polymer value chain; and that the relationship between these must somehow be weighted to enable value judgements about possible growth scenarios to be made. This weighting takes place in section 3.1.2, where out of the consistency matrices of influencing factors (Figures 3-3 to 3-5) three scenarios emerge: WITHOUT P&M (policies and measures); WITH P&M and HIGH GROWTH.

Projections for production volumes of bio-based polymers were then made by considering information on the supply of polymers according to company growth expectations, comparing this with market demand by application area, and developing time series that take these supply and demand expectations as well as economies of scale into account. Results obtained (Chapter 3.4) show that with a growth rate in the order of 40-50% p.a. for 2000-2010 (i.e. factor 20 to 40 growth between 2002 and 2010); and 6-12% p.a. for 2010-2020, **growth rates of bio-based polymers are substantial**, providing strong evidence that this is an emerging business. Bio-based polymers will continue to penetrate the polymer market. In absolute terms, they are projected to reach **a maximum of 1 million tonnes by 2010** in the scenario WITH P&M and max. **1.75-3.0 million tonnes by 2020** in the scenarios WITH P&M and HIGH GROWTH respectively. While these are sizable quantities a **one million tonne growth in bio-based polymers corresponds to a 10 million tonne growth in petrochemical polymers**. **Thus, the market share of bio-based polymers will remain very small,** in the order of 1-2% by 2010 and 1-4% by 2020. For 2020 with the HIGH GROWTH scenario, somewhat higher market shares are reached: bio-based polymers increase by a maxiumum of 3,000 t while petrochemical polymers increase by 25,000 t; the difference still being a factor of 8.

Going one step further and comparing the maximum (technical) substitution potential estimated in Chapter 2.8 with the projected volume of bio-based polymers according to the three scenarios in Chapter 3.4 (see Table 5.1), it is apparent that there is a sizeable gap between the share of bio-based polymers according to the maximum substitution potential (33%), and the projected share, even in the case of the HIGH GROWTH scenario (4.3%; thus a gap of 29%). This firstly shows that there is, in principle, substantial scope for further growth beyond the HIGH GROWTH scenario. Secondly it strengthens the conclusion drawn above that bio-based polymers, while growing rapidly in absolute volumes, will **not provide a major challenge, nor present a major threat, to conventional petrochemical polymers**. On the other hand it should firstly be noted that this report discusses exclusively the possible developments in Europe (EU-15) while bio-based polymers **might enjoy higher growth rates in other world regions** (such as Asia). Secondly, it must be recalled here that this report is based on information on *commercialised and emerging* bio-based polymers. **Other bio-based polymers** which are currently in an earlier phase of R&D are not taken into account even though some of them might be produced on a respectable scale towards the end of the projection period of this report (year 2020). Bio-based chemicals that are not used for polymer production (e.g. solvents, lubricants and surfactants and other intermediates and final products) are outside the scope of this report; if they develop favourably, this could reinforce also the growth of bio-based polymers.

Table 5-1: Projected market share of bio-based polymers according to three scenarios and the maximum (technical) substitution potential

Production in million tonnes	2000	2002	2010	2020
Petrochemical polymers, production in 10^6 t	44.9	47.3	57.4	70
Bio-based polymers, production in 10^6 t				
- Without P&M	0.018	0.025	0.05	0.875
- With P&M	0.018	0.025	1.00	1.75
- High Growth	0.018	0.025	1.00	3
- Max substitution	-	15.61	18.94	23.1
Market share of bio-based polymers, %				
- Without P&M	0.04%	0.05%	0.09%	1.25%
- With P&M	0.04%	0.05%	1.74%	2.50%
- High Growth	0.04%	0.05%	1.74%	4.29%
- Max substitution	-	33.00%	33.00%	33.00%

Further considering the growth projections, it may be concluded that while petrochemical polymers will continue to have a much stronger position in the polymers market, the bio-based polymers industry is an emerging competitive business which is considered to have a better chance in the growth phase of polymers (as a group of materials), i.e. in the now/near-term future, than in the maturity stage (medium/long-term future). Thus, time may be a critical issue in establishing a favourable environment for bio-based polymers should the EU wish to strengthen its global competitive basis in this industry.

5.4 Environmental, economic and societal effects

Energy and GHG emission savings in specific terms were found to be 20-50 GJ/t polymer and 1.0-4.0 t CO_{2eq}/t polymer respectively (in Chapter 4.2.1). **Bio-based polymers are thus very attractive in terms of specific energy and emissions savings. In absolute terms, savings are rather small:** as a proportion of the total EU chemical industry, energy savings amount to **0.5-1.0% by 2010, up to 2.1% by 2020**; compared to the total EU economy the figures are **0.1%** until 2010 and **0.2%** until 2020 (Chapter 4.3.1). Greenhouse gas emissions savings amount to **1-2% by 2010, up to 5% by 2020**; compared to the total EU economy the figures are **0.1%** until 2010 and **0.2%** until 2020. Bio-based polymers therefore cannot offset the additional environmental burden due to the growth of petrochemical polymers (which is understandable in view of a gap of a factor of about 20 to 40). It is also out of the question that, within the next two decades, bio-based polymers will be able to meaningfully compensate for the environmental impacts of the economy as a whole. However, it is not unthinkable that the boundary conditions for bio-based polymers and the energy system will change dramatically in the **decades after 2020, e.g. due to substantially higher oil prices**. If, *ceteris paribus*, bio-based polymers would ultimately grow ten times beyond the HIGH GROWTH projection for 2020 (i.e., to about 30 million tonnes), this **could avoid half of the chemical sector's current GHG emissions**, without accounting for major technological progress that should have been made until then. These considerations for the very long term do not justify any concrete (policy) action today, they are rather intended to demonstrate the implications of the comparatively low production volumes until 2020 (compare also per capita values in Table 3-3).

While bio-based polymers can contribute to energy savings and GHG emission reduction compared to petrochemical polymers, their production obviously entails the use of land. The results of the calculations on land use requirements (Chapter 4.3.1) show that by 2010 a maximum of 125,000 ha may be used for bio-based polymers in Europe and by 2020 an absolute maximum of 975,000 ha (High Growth Scenario). Comparing this with total land use in EU-15 for various purposes, shows that if all bio-based polymers were to be produced from wheat, land requirements range from 1% WITH P&M to 5% in the case of HIGH GROWTH. As a proportion of total cereals these figures are a factor 2 lower. Compared to total set-aside land (1997 values), the percentage of land required ranges from 3.6% to 15.4%; as a percentage of industrial crops the range is similar. **Bio-based polymers are thus seen to have modest land requirements and will not cause any strain within the EU on agricultural land requirements in the near future. There could, however be some conflict of interest with bioenergy crops for utilisation of set aside or industrial crop land after 2010 in the case of HIGH GROWTH.**

One socio-economic effect of the growth of bio-based polymers will be to generate employment in the agricultural industry by utilising land that will otherwise be set aside. Net employment effects for the three scenarios are as follows: WITHOUT P&M, 500 extra fte will be employed; WITH P&M, 1000 fte; and for High Growth, 4500 fte. **The employment potential in the agricultural sector is thus very limited**.

Summarising the potential environmental and socio-economic effects it may be concluded that while environmental effects in specific terms are high, effects in absolute terms relative to those of total industry or society are low. Job creation potential is also low. It must be emphasized that these relatively low contributions have their reason in the comparatively low production volumes of bio-based polymers until 2020. Even so, the societal ramifications may be significant and positive in the “green chemistry” arena, for education, for the image of the companies involved (including producers and users of bio-based polymers) and ultimately also for the innovation climate.

An additional positive impact of bio-based polymers is that coupled with the growth and development of the bio-based polymers market is a reduction in the economic risk/uncertainty associated with reliance on petroleum imported from unstable regions such as the Middle East, Angola, and Venezuela. In many ways, the volatility of oil price has as great an economic impact as the absolute price of oil. Biobased products may have their own price volatility due to natural factors, but they may still usefully serve as a hedge against uncertainty in oil prices. This point has been studied in detail elsewhere (see e.g. Lovins et al., 2004) and is indeed one of substantial weighting in the global political arena today.

6. Policy recommendations

The preceding chapters have shown that the main societal benefits of bio-based polymers are

- the reduction of potential environmental impacts (studied for energy and greenhouse gas emissions),
- the exploitation of new synergies and collaborations with other emerging areas, most notably with biotechnology[44] and nanotechnology but also with established polymer chemistry,
- an – albeit low - increase of income and employment in the agricultural sector,
- opportunities for growth and improved products in many important areas of polymer use, especially in packaging, automotive, electrical & electronics and the agricultural sector and
- the contribution to a positive attitude towards technological innovations that serve societal goals.

While only a limited number of quantitative indicators (mainly energy, GHG emissions, land use and employment) could be studied in this report it is important to realise that no obvious disadvantages could be identified for bio-based polymers. According to the insight gained in this study bio-based polymers are fully consistent with the European Union's "Integrated Product Policy" (IPP)", the central aim of which is that "the products of the future shall use less resources, have lower impacts and risks to the environment and prevent waste at the conception stage" (IPP, 2001). Given this outcome which is, in principle, clearly in favour of bio-based polymers, the next questions seem to be

1. whether bio-based polymers need any policy support and if so;
2. which objective(s) (e.g. competitiveness, diffusion of consumer acceptance) should be pursued and how the targets should be set;
3. which Policies and Measures (P&Ms) should be implemented toward this end; and
4. at what level bio-based polymers should be supported.

This chapter cannot give any final answers to these four questions but it can provide some hints and indications.

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[44] For the application of biotechnology for the production of bulk chemicals, the expression "White Biotechnology" has been coined (see for example Sijbesma, 2003).

6.1 Considerations about the need of policy support, an adequate support level and the implications of implementation

Both the question as to whether bio-based polymers require any policy support (Question No. 1), and if so, at what level (Question No. 4), can be answered by taking into account the developments and requirements in other policy domains. Both questions are related to a requirement that any policy or measure should fulfill, i.e. to maximise cost effectiveness and to avoid "free riding". The term "free riding" is, in this particular case, used to describe the problem of providing benefits to induce behaviour in a recipient who would have acted in the desired way *without* inducement. Freeriders reduce the cost-effectiveness of a measure (in the extreme case: zero cost-effectiveness).

A first attempt to answer Question No. 1 and No. 4 has been made in Section 4.5.2 by using the public expenses for supporting green electricity from biomass to estimate the equivalent for bio-based polymers. Assuming a comparable funding level based on the amount of primary energy saved, we estimate an equivalent level of financial support of 0.1-0.2 EUR per kg of bio-based polymer (see Section 4.5.2). This means that **the society's willingness to pay for green electricity** (from biomass) **can translate into a level of financial support that would help to improve the competitiveness of bio-based polymers.**

With regard to implementation, a few practical aspects need to be taken into account. Firstly, a suitable way of **administrative implementation** would need to be found. To this end, one could possibly adopt similar approaches as those implemented for green electricity (feed-in tariffs or tradable certificates). If the idea is followed that the degree of reduction of environmental impacts should determine the level of the financial support (as is the case for feed-in tariffs or tradable certificates), then this could require quite an ambitious monitoring and verification system. In view of the complexity of chemical processes and products and the restrictions to the information flow for reasons of confidentiality, this may lead to a considerable administrative burden (for both the company and the government) and hence to rather high transaction cost. On the other hand, the limited number of actors and facilities now and also in the medium-term future helps to limit the transaction cost and makes this area in principle amenable to well-targeted policies . While it is difficult to make a tradeoff, it seems safe to say that the **transaction cost will be higher for bio-based polymers than for green electricity**. The high administrative effort could possibly even make implementation of such a model rather unattractive for some companies of the bio-based polymer industry.

The latter disadvantages are not present in other forms of financial support, such as a **reduction of VAT rates** (Section 4.5.2), with the disadvantage of lower specificity (no distinction between differences in energy savings across the different types of bio-based polymers). Apart from lower transaction cost (in regular implementation) a reduction of VAT rates might also have the advantage of a lower risk of litigation.

A thorough discussion about reduction of VAT rates would actually require a comprehensive overview of all existing fiscal measures and subsidies that may ultimately influence the final prices of both bio-based polymers and petrochemical polymers in a decisive way and hence also clearly infuence the relative competitiveness. While it is not part of this project to study these issues, it seems important to point out two areas which may require further investigations in this regard. These are firstly

subsidies to the agricultural sector and secondly **tax exemptions for the feedstock use of fossil fuels**. While the first is not expected to have any major impact on the current final prices of bio-based polymers (due to the world market price level and the low cost share of agricultural inputs to the process chain), the latter could have a dampening effect on the price level of petrochemical polymers.[45] Assuming full tax deduction of the naphtha feedstock only (avoided taxes amounting to about 2 EUR/GJ naphtha[46]) and combining this with the heating value of a polymer (assumed: polyethylene, PE) or – alternatively – with the cradle-to-factory gate energy use of this polymer – leads to an equivalent of **0.10 to 0.15 EUR/kg** polymer. **This is a conservative[47] first estimate which should be checked and possibly corrected**. If it proves to be correct, then

- **the current financial support for petrochemical polymers by tax exemption of the feedstocks is in the same range as the level of financial support discussed above for bio-based polymers.**
- **only after introduction of a similar support for bio-based polymers as currently received by petrochemical polymers, a level playing field would be established.**
- the current production of 45 million tonnes of petrochemical polymers would be equivalent to a **hidden subsidy of 4.5-6.75 billion EURO and the additional growth by 2020 would imply an extra 1.25-1.9 billion EURO until 2010 and 2.5-3.8 billion EURO until 2020.**

Further analysis is recommended on these issues.

A limiting factor for future policy for bio-based polymers could be its **affordability** if, after some years, **high production volumes** are reached. A first lower estimate of the cost of supportive P&Ms for bio-based polymers in line with the discussion above can be made by multiplying a VAT reduction of 4% with the production value. For the latter, (upper) estimates amounting to 1-2 billion EUR by 2010 (scenarios WITH P&M and HIGH GROWTH) and 3-6 billion EUR by 2020 (scenario HIGH GROWTH) (discussed in Section 4.5.1). This results in total expenditures (or rather: lost state income) of 40-80 million EUR by 2010 and 120-240 million EUR by 2020. In order to draw a first conclusion (beyond the scope of this study), these values, which refer to a very successful development of the bio-based polymer industry, should be compared with government spendings for other sectors including the tax exemptions for fossil feedstocks. **If the estimates for the latter in the preceding paragraph prove to be in the right ballpark, then the potential hidden expenses for bio-based polymers quoted above do not seem prohibitively high.**

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[45] This statement should not be interpreted as recommendation to remove the tax exemption of petrochemical feedstocks if important competitors in non-EU countries have similar policies in place since this could seriously affect the competitiveness of the European chemical industry.

[46] Estimated on the basis of IEA (2000b).

[47] The estimate is conservative because the gross feedstock input to steam crackers is higher than the total amount of high-value chemicals produced in steam crackers plus the process energy to drive the cracking process. The reason is that fuel byproducts are also produced and returned to the refinery.

Except for those estimates in the last paragraph the considerations in this Section (6.1) do not build on long-term projections for production volumes and future environmental effects and they are therefore *not* subject to the Note of Caution at the very beginning of this report. Neverthess it is recommended that further investigations be conducted in order to check and substantiate the estimates made in this section.

6.2 Overview of possible policies and measures to promote bio-based polymers

Using the policies and measures (P&Ms) for bioenergy as a starting point, the discussion in the preceding section revolved around different ways of providing tangible financial support to the emerging bio-based polymer industry. While these P&Ms are rather expensive, there are other possibilities to promote bio-based polymers that differ also with regard to their objectives. These options are discussed in this section, thereby linking up with the question of which objective(s) should be pursued and with which targets (see above, Question No. 2) and which policies and measures (P&Ms) should be implemented to achieve these objectives (Question No. 3).

A wide range of P&Ms can be implemented in order to increase the market share of bio-based polymers. Table 6-1 provides an overview of policies and measures (P&Ms) for bio-based *materials* in general (referred to as renewable raw materials, RRM), which is equally relevant to bio-based polymers. Apart from bio-based *polymers* the group of RRMs comprises bio-based lubricants, solvents and surfactants. An earlier version of Table 6-1 was originally prepared by the Working Group “Renewable Raw Materials” (RRM Working Group) under the European Climate Change Programme (ECCP). The RRM Working Group also prepared an overview of P&Ms for bio-based *polymers*; this overview is included in the appendix (Appendix 4) and not in this chapter since it is strongly directed towards *biodegradable* polymers while this study deals with bio-based polymers – whether they are biodegradable or not.

Table 6-1: Suggested general policies and measures to promote wider use of renewable raw materials (RRM) *) (modified table from ECCP, 2001)

	Suggested policies and measures	Objective
1.	Medium and longer term RD&D (research, development and demonstration)	Improve scope of application as well as technical and economic performance by basic and applied RD&D. Provide a range of (bio-degradable among others) additives for bio-based polymer processors
2.	Standardisation	Harmonised standards (e.g. on composting)
3.	Public procurement	Facilitating commercialisation, creating economies of scale and contributing to higher awareness
4.	Limited fiscal and monetary support (e.g. reduced VAT rate)	Facilitating commercialisation, creating economies of scale
5.	Inclusion in the CAP (Common Agricultural Policy)	Secure, sufficient and stable supply of biomass feedstocks
6.	Inclusion of RRM in climate and product policy	CO_2 credits for manufacturers/users of RRMs, e.g. represented by tradable Green Certificates
7.	Adaptation of waste legislation and waste management	Improve infrastructure for separate collection and treatment of biodegradable materials (especially polymers and financial incentives for the consumer, lower waste costs for consumers)
8.	Awareness raising among consumers, processors and producers (top management) of RRM	• Create a wide public understanding about the possibilities and the environmental benefits of RRMs (conferences, workshops, information campaigns, courses, seminars and giving companies the opportunity to learn from positive examples) • Provide for coherent approach and political attention for the short, medium and long term, possibly by means of a European Commission inter-service task force

*) RRM is used here as a synonym for bio-based *materials*. Apart from bio-based polymers the group of RRMs comprises bio-based lubricants, solvents and surfactants.

In the following the P&Ms proposed in Table 6-1 will be briefly discussed. Recommendations will be given for bio-based polymers, thereby linking up with relevant activities in the EU and in non-EU countries.

1. **Medium and longer term RD&D (research, development and demonstration)** Further RD&D into bio-based polymers, including critical technologies such as biotechnology and nanotechnology, is crucial. The European Commission is continuing its RD&D funding in these areas under the 6th Framework Programme. It will have to be critically assessed whether the change in the funding strategy when shifting from the 5th to the 6th Framework Programme was justified and which conclusions can be drawn. In this context, the **experience in other countries, especially in the U.S., should be taken into account,** where sizable awards have recently been granted to consortia of large scale bio-based polymer producers, universities, research organisations and SMEs (e.g. the Integrated Corn-Based Bioproducts Refinery (ICBR) project with partners DuPont, NREL, Diversa Corporation, Michigan State University and Deere & Co. (NREL, 2003). More information about the U.S. policy on bio-based products can be found in Appendix 5.

2. **Standardisation**
   By defining and enforcing minimum quality levels for products and processes, standardisation is a necessary condition for the creation of a large common market that is an important requirement to realize economies of scale. For example, in the past 1-2 years much effort has been put into the standardisation of compostability. While standardisation is undoubtedly important, it requires **little to no direct input by policy makers** (which is the focus of this Chapter 6).

3. **Public procurement**
   Public procurement has been successfully applied to environmentally benign products. Within Europe, ample experience seems to be available especially in **Switzerland** where a contact point has been set up for environmental public procurement at the federal level[48] and where several initiatives exist at the municipal level. In the U.S, the EPA Environmentally Preferable Purchasing Program has been set up (see Appendix 5). Under sponsorship of the **EPA Purchasing Program**, the U.S. Department of Agriculture, and the National Institute of Standards and Technology (NIST), a calculation tool called **BEES** (Building for Environmental and Economic Sustainability) has been developed that follows the principles of environmental life cycle assessment and is meant to help in making federal purchase decisions (BEES, 2003). **In BEES, special attention is being paid to bio-based products**.

4. **Limited fiscal and monetary support (e.g. reduced VAT rate)**
   As discussed above in Section 4.5.2 and Section 6.1, a fiscal or monetary support of 0.1-0.2 EUR/kg bio-based (for the long term and for the short term respectively) would be equivalent to the widely accepted public spending on green electricity. It would help **to improve the competitiveness of bio-based polymers** and is recommended for further analyses. In this context, also tax exemptions for the **feedstock use of fossil fuels** should be studied with regard to their effects on the relative competitiveness of bio-based versus petrochemical polymers.

5. **Inclusion in the CAP (Common Agricultural Policy)**
   Pursuing the objective of a secure, sufficient and stable supply of biomass feedstocks. The inclusion of bio-based polymers (as part of RRM) in the CAP can be expected to become particularly important when bio-based polymers start to be produced in very large volumes, e.g. beyond 1 million tonnes. In the meantime **the policy pursued for set-aside land, i.e. to reserve it for bioenergy, may have to be rethought**. The reason is that recent analysis by Dornburg et al. (2003) has shown **bio-based materials to be more attractive in terms of efficient land use than bioenergy**. It is recommended to policy makers that they consider this insight in their deliberations.
   Another, largely independent, recommendation is to make use of the experience gained by the **U.S. Department of Enery and the U.S. Department of Agriculture** (USDA) since the start of their U.S. 2020 Vision of Plant/Crop-Based Renewable Resources (DOE, 1998; 1999; compare Appendix 5).

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[48] In German: Fachstelle umweltorientierte öffentliche Beschaffung.

6. **Inclusion of RRM in climate and product policy**
   As indicated in Section 4.5.2 and Section 6.1, tradable **Green Certificates** could be a suitable instrument to incorporate bio-based polymers into **climate policy**. As a precondition, a trading scheme with Green Certificates would first have to be established. It seems recommendable to investigate this further and to make also comparisons with other instruments (e.g. reduction of VAT etc.). Compared to the inclusion in the Green Certificate Scheme, integration of bio-based polymers in the EU Emission Trading Scheme (EU ETS) is expected to be relatively unattractive for the bio-based industry, due to the comparatively low value of the so-called emission allowances.
   Regarding the EU **product policy**, no recommendation can be made at this stage since it is not clear what shape it will take and how bio-based polymers could be included.

7. **Adaptation of waste legislation and waste management**
   Adaptation of legislation in the waste sector as put forward under the ECCP (2001) mainly concerns the permission to compost biodegradable polymers. There is serious **controversy** between stakeholders about the advantages and disadvantages of composting and digestion on the one hand and incineration on the other. Apart from GHG emissions and energy use, other parameters such as nutrient recycle and natural carbon cycling and the quality and fertility of soil play a role. Especially in the latter areas there are **serious knowlegdge gaps**; it is recommended to close these before drawing policy conclusions.

8. **Awareness-raising among consumers, processors and producers for RRM**
   It is important to ensure a coherent approach to RRM in the short, medium and long term, possibly by means of a European Commission inter-service task force. Such a task force should include representatives of DG Enterprise, DG Agriculture, DG Transport & Energy and DG Environment. A European Commission inter-service task force could act as contact for key players and similar establishments in other countries/regions, such as the BT Strategy and Biomass Nippon in Japan and the U.S. 2020 Vision of Plant/Crop-Based Renewable Resources (DOE, 1998; 1999). It should be checked whether the networks of government, industry and academia that have been established in Japan and the U.S. can serve as a model also for the EU (compare Appendix 5). The RRM Working Group could be associated to this inter-service task force and could play a very useful role by creating the direct link to industry, institutes, stakeholders and NGOs. Possibly the co-operation of the networks in Japan, the U.S. and Europe should be stimulated.

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8. Abbreviations

a	year
CH_4	methane
CO_2	carbon dioxide
d	day
ECCP	European Climate Change Programme
EPS	expanded polystyrene
eq.	equivalents
g	grams
GHG	greenhouse gas emissions
GJ	Gigajoule (10^9 joules)
GM	Genetic modification, genetically modified
ha	hectare
HDPE	high density polyethylene
kg	kilogramme
kt	kilotonne
l	liter
LCA	life cycle assessment
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
MD	Machine Direction (test method for elongation, tensile strength)
MJ	Megajoules (10^6 joules)
Mt	Megatonne (10^6 tonnes)
m^3	cubic metre
MSWI	municipal solid waste incineration plant
N_2O	nitrous oxide
P&M	Policies and Measures
PA	polyamide (nylon)
p.a.	per annum
PCL	polycaprolactone
PE	polyethylene
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoates
PHB	polyhydroxybutyrates
PJ	petajoule (10^{15} joules)
PLA	polylactides
PO_4	phosphate
PP	polypropylene
PS	polystyrene
PUR	polyurethane
PVOH	polyvinyl alcohol
RRM	Renewable raw material
R&D	Research and Development
SO_2	sulphur dioxide
t	metric tonnes
Tg (GTT)	Glass Transition TemperatureTm Crystalline Melt Temperature
TD	Transverse direction (test method for elongation, tensile strength)
TJ	tetajoule (10^{12} joules)
t.p.a.	metric tonnes per annum

TPS	thermoplastic starch
, (comma)	thousand separator
. (point)	decimal separator

Conversion factors

1 metric tonne = 2205 pounds
1 metric tonne = 1.102 tons
€ 1 = US $ 1.1 (unless otherwise stated)

Country Groupings

EU-15	European Union-15: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.
EU-25	EU-15 plus 10 New Member States: Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, the Slovak Republic and Slovenia
W.Europe	Faroe Islands, EU-15, Gibraltar, Iceland, Malta & Gozo, Norway, Switzerland

9. Appendices

Appendix 1: 2001-2002 Potential Applications for Nodax® based on Product Advantages (world-wide market potential, % of total within application).

Table reprinted with permission from Procter & Gamble.

Application	**Description/ (Examples)**	**Market Potential(% of total)**	**Market Potential (t.p.a. of compounded resin)**	**Specific Nodax™ advantages that provide market potential, either alone or in combination with other biopolymers or cellulosics**
Ag Film	Weed & moisture control *(mulch film)*	15	41,000	Product benefits include a tillable/biodegradable film. Blends with starch to achieve cost/performance target. Bans on Starch/PE versions and burning waste film open market opportunity.
Binders for Nonwovens	*Paper towels, interfacing, paper*	10	1800	Performance, disposal (including flushability), blendability. Nodax™ fibers as well as Nodax™ resin.
Coated Corrugated	*Shipping cartons, display cartons and stands*	5	56,800	Repulpability, barrier properties, and printability offer niche opportunities in the coated linerboard area.
Coated Paper	Printed materials, linerboard, laminates *Detergent boxes, candy bar packages*	5	68,200	Regulations in Asia requiring compostable food packaging open large market for "lunchboxes" and other paper/poly food packaging. Replace OPP on printed cartons (used for moisture and odor barrier.)
Fast Food Industry **Cups** **Plates** **Utensils**	Coating/lamination to starch foam articles, or coated paper articles.	10	720,000	Product benefits are same as the above. Clearest market opportunities are in the closed loop environment—i.e. Disney, cruise, etc.
Fertilizer coating or use in Japan rice paddies	*Slow release, encapsulated pellets*	100	454	Anaerobic degradability is a key need in this area. This effort would co-evaluate potential for broader fertilizer/delivery system applications.
Flexible Packaging	Flexible plastic food containers *(oily snacks)*	5	36,200	Blends with PLA to enhance PLA's suitability for this market (makes it softer, better barrier, and more readily compostable and biodegradable).

Application	**Description/ (Examples)**	**Market Potential(% of total)**	**Market Potential (t.p.a. of compounded resin)**	**Specific Nodax™ advantages that provide market potential, either alone or in combination with other biopolymers or cellulosics**
Flushables	*Tampon Applicator* *Pad Back Sheet* *Baby Wipes* *Ostomy bags*	40	8100	Flushability provides consumer benefits of convenience, discretion and hygiene; Nodax™ uniquely provides flushability for anaerobic/septic systems.
Islands in the Sea Fibers	Artificial Leather *Specialty fibers & Nonwovens*	75	3400	Used as bicomponent, coextruded fraction which is later digested and not part of final product. Digestibility without use of chemical solvents (TCE), resulting in neutral, innocuous effluent. Cost savings and environmental benefit.
Lawn, Leaf and Compostable Bags	*All sizes*	20	7300	Product benefits include odor control and compostability.
Synthetic paper	Commercial papers *(prime & in-mold labels, flexible packaging)*	3	1700	Product benefits include printability and environmental impact; there is potential to reduce Nodax™ costs and improve cost competitiveness through filler addition.
Thermoformed products	Disposable containers & tubs *(dairy products)*	5	227,200	Product benefits include biodegradability and barrier properties. Regulations requiring composting of food waste open market opportunity.
US Navy Cup	This is a starting point for other Government required "green" or marine degradable materials targeted by EO 13101	100	32	Competitive advantage in affinity to cellulose and hot beverage compatibility. Product benefits include reduced environmental impact, marine degradability, printability, and cup reuseability. Budget for finished goods targeted by the US EO 13101 is $1.5 billion. Specific opportunities are still to be determined. This application helps validate benefits and opportunities in other paper coating markets.
USPS one-way bag	Replace PP Woven Bag.	30	2300	Product benefits include compliance with overseas disposal requirements as well as EO13101.
TOTAL LEAD POTENTIAL		N/A	1,174,486	Actual t.p.a. that is Nodax™ will vary by application, but in total is estimated at 40%.

Appendix 2.1: Property comparison table for some bio-based polymers

Polymer name	Starch-poly(ε-caprolactone) blend	Poly(lactic acid) *or* Poly(lactate)	Poly(3-hydroxy-butyrate-*co*-3-hydroxyvalorate)	Poly(3-hydroxy-butyrate-*co*-3-hydroxyhexanoate)	Cellulose hydrate
Acronym	Starch-PCL	PLA	P(3HB-co-3HV)	P(3HB-co-3HHx)	Cellophane
Chemical properties					
Polymer^a structure	polysaccharide	aliphatic polyester	aliphatic copolyester	aliphatic copolyester	Polysaccharide
Molecular weight (10^3 Dalton)		100-300	200-400		
Crystalline content (%)		10-40	30-80		
Physical properties					
Melt flow rate (g/10 min)		-^{aa}		0.1-100	
Density (g/cm^3)	1.23	1.25	1.23-1.26	1.07-1.25	1.45^4
Transparency (%)		0.7	-		
Haze^b(%)		1.5-3.0	-		1-2^4
Mechanical Properties					
Tensile strength at yield (MPa)	31	53		10-20	
Elongation at yield (%)	900	10-40; 10-100^{ab}		10-25	
Flexular modulus (MPa)	180	350-450	40		
Thermal properties					
Heat deflection temp (°C)		40-45; 135^{ac}		60-100	
VICAT Softening point (°C)		close to GTT		60-120	
Melting point (°C)	64	58-63^{ad}	171-182	80-170	
Glass transition temp (°C)		55-65	5-70		
Chemical Resistance					
Mineral oil		good	good		
Solvents		poor	poor		
Acid		avg/poor	poor		
Base		avg/poor	poor		
Barrier Properties					
CO$_2$ permeability (cm^3/m^2/day, 25μm, 1atm)		51000			
O$_2$ permeability (cm^3/m^2/day, 25μm, 1atm)		4400			
WVTR (g/m^2/day, 50μm, 23°C, 90% humidity)		3400			

Brandrup, 1999; Boustead, 2002; Gruber et al., 2002; Garlotta, 2001; Metabolix 2002; Plastics Technology 2002; Leaversuch, 2003.

[a] bio-based polymer only in case of blend

Appendix 2.2: Property comparison table for some potentially bio-based and main petrochemical-based polymers

Raw material basis	Petchem-based	Potential bio-based monomer	Potential bio-based monomer	Potential bio-based monomer	Potential bio-based monomer	Potential bio-based monomer	Petchem-based	Petchem-based	Petchem-based	Potential bio-based monomer	Petchem-based	Petchem-based
Polymer name	Poly (ethylene terephthalate)	Poly (trimethylene terephthalate)	Poly (butylene terephthalate)	Poly (butylene succinate)	Poly (amide)-6 (nylon-6)	Poly (amide)-9T (nylon-9T)	Poly (amide)-6,6 (nylon-6,6)	Poly (carbonate)	Poly (propylene)	Poly (urethane)	Low density poly (ethylene)	High density poly (ethylene)
Acronym	PET	PTT	PBT	PBS	PA 6	PA 9T	PA 6,6	PC	PP	PUR	LDPE	HDPE
Chemical properties												
Polymer structure	aromatic polyester	aromatic polyester	aromatic polyester	aliphatic polyester	poly-amide	poly-amide	poly-amide	poly-carbonate	poly-olefin	poly-urethane	poly-olefin	poly olefin
Molecular weight (10^3 Dalton)	170-350											
Crystalline content (%)	> 30											
Physical properties												
Melt flow rate (g/10 min)									3[c]		0.3	0.5
Density (g/cm^3)	1.40	1.35	1.34	1.25	1.13		1.14	1.2	0.91	1.45	0.92	0.95
Transparency (%)	4.1											
Haze[b] (%)	2-5				2-3[a]		2-3[a]		1-4	1-2		
Mechanical properties												
Tensile strength at yield (MPa)	72.5	67.6	56.5		80		82.8, 90	65	28		26	60
Elongation at yield[d] (%)					50-100		20		500		530	300
Flexular modulus (MPa)	3110	2760	2340		2410		2830	2350	1690			
Thermal properties												
Heat deflection temp (°C)	65	59	54		55-75[3]		90	129				
VICAT softening point (°C)	79											
Melting point (°C)	265	228	222-232	90-120	220		265		168		115	135
Glass transition temp (°C)	80	45-65, 80[e]	30-50	-45 to -10	40-87		50-90		-17 to -4			
Chemical Resistance												
Mineral oil	good		good									
Solvents	good		good									
Acid	avg											
Base	poor											
Barrier Properties												
CO_2 permeability (cm^3/m^2/day, 25µm, 1atm)	240											
O_2 permeability (cm^3/m^2/day, 25µm, 1atm)	95	228	255									
WVTR (g/m^2/day, 50µm, 23°C, 90% humidity)	23	59	54									

[1] Refs: Hwo & Shiffler (2000); Grothe (2000); Brandrup et al. (1999); Leaversuch (2002); Galactic (2003); Chuah (1999); Morgan (1998); Brydson (1989); Brandup (1989); Brikett (2003); Kubra Kunstoffen (2003); Kawashima et al. (2002); deKoning (2003); Plasticbottle Corp (2003).

[a] Gen. fig. for nylons; [b] Biaxially oriented films; [c] ATSM D 1238, 230°C; [d] ASTM D 882; [e] lower range is for resin, higher figure is for drawn and textured fibre.

Appendix 2.3: Property comparison table for commercialized 'GreenPlas' in Japan: bio-based and petrochemical-based biodegradable polymers (BPS, 2003a)

Properties / Classification		Thermodynamical Prperties								olten-Sta	Mechanical Properties						Gas Perm
		Amorphous Phase			Crystalline Phase			Bulk	Combustio		Stress-Strain Properties				ardness(*	mpactnes	
		Tg(*b) ℃	HDT(*c) ℃	Vicat(*d)	Tc(*e) ℃	Tm(*f) ℃	Xc(*g) %	d(*j) g/cm3	C(*h) Cal/g	MFR(*j) g/10min	ending(*k (MPa)	stress(*l (MPa)	TS(*m) (MPa)	EL(*n) %	(R/Sh)	Izod(*p) J/m	Water (*q)
hard type	PHB	4	145/87	141		180		1.24			2,600	2,320	26	1.4	73/	12	3.6
	PHB/V					151		1.25			1,800	800	28	16		161	
	PLA	58-60	/55	58		160-170		1.26	4,000		3,700	2,800	68	4	115/79	29	4
			/66	114		160-170					4,710		44	3		43	
			/57	113		160-170					2,400		39	220		65	
		60-62				172-178				0.5-3.0	3,500		63	2-5			
		60-62				150-170				5-12	60		59	2-5			
		45-55			not observed					50-100	2,250		45	1-2			
	CA		77/53	111				1.25			1,100	240	27	62		120	
	PVA	74			175-180	200-210		1.25	6,000	0.5-20		39	1	2		13	6
(ref)	GPPS	80	/75	98				1.05	9,600		3,400	2,500	50	2	120/	21	4
soft type	PCL	-60	56/47	55		60		1.14			280	230	61	730		n b	23
	PBS	-32	97/		75	114	35-45	1.26	5,640	1.5	600		57	700		30	18
		-32	97/		76	115	35-45	1.26	5,640	25	685		21	320			
		-32	97/		88	115	35-45	1.26	5,640	4.5	685		35	50			
		-32				112		1.26			590	510	73	550		nb	
		-45				87		1.25			250	230	53	560		nb	
	PBSA	-45	69		50	94	20-30	1.23	5,720	1.4	325		47	900			
		-45	69		53	95	20-30	1.23	5,720	25	345		34	400			
	PBSC	-35	/87			106		1.26			510	330	46	360	84/	96	27
	PEST					200		1.35		11	2,000		55	30			1.6
	PBAT	-30		80		115		1.26				100	25	620	/32	45	5
	PTMAT	-30				108		1.22		28			22	700			13.8
	PES	-11				100	40	1.34			750	550	25	500		186	11
	Starch	-54	68					1.17	4,500	6		280	17	670			
								1.25				180	30	800			22
(ref)	HDPE	-120	82		104	130	69	0.95	11,000	2? 230C)	900	1000	70	800		nb	
(ref)	LDPE	-120	49	96	80	108	49	0.92	11,000	2? 230C)	150	420	12	800	/48	n b	0.085
(ref)	PP	5	110	153	120	164	56	0.91	10,500	4? 230C)	1,400	1,100	32	500		20	0.12
(ref)	PET		/67	78		260		1.38	5,900			2,650	57	300	108/	59	0.5

Key to table (see previous page for table)

(*a) based on Catalogue Data Base
(*b) Tg Glass Transition Temperature based mainly on DSC-Method
(*c) HDT Heat Distortion Temperature based on JIS K 7207 **/** = lower loading/higher loading
(*d) Vickers Softening Point based on JIS K 7207
(*e) Tc Maximum Crystallization-Rate Temnperature based on DSC-Method
(*f) Tm Crystallite-Melting Temperature based mainly on DSC-Method
(*g) Xc Degree of Crystallinity
(*h) C Heat of Combustion
(*i) d Density
(*j) MFR Melt Flow Ratio Unit:g/10min 190deg.C Load 2.16kg
(*k) Bending Elascity based on JIS K 720. Unit:Kgf/cm2 (*9.8/100=MPa)
(*l) YS Yield Stress based on JIS K 7213. Unit:Kgf/cm2 (*98/100=MPa)
(*m) TS Tensile Strength based on JIS K 7213. Unit:Kgf/cm2 (*98/100=MPa)
(*n) EL Elongation based on JIS K 7213. Unit:
(*o) Hardeness. Unit:R/Sh
(*p) Izod Impactness based on JIS K 7110. Unit:J/m. Note n.b non brittle
(*q) based on JIS Z 0208. Unit:g·mm/m2/24 (normalized to 1mm-unit case)
(*r) based on MOCON-Method. Unit:cc·mm/m2/24 /atm (normalized to 1mm-unit case)

Appendix 2.4: Key properties and applications of bio-based polymers

Polymer	**Main types (incl blends)**	**Density (g/cm^3)**	**Advantageous properties**	**Disadvantageous properties**	**Applications**	**Substitution on material / application basis**
BIO-BASED						
Starch polymers	TPS; blends with PCL, PVOH, PBS, PBS-A; modified starch incl. starch acetate; starch ester; starch-cellulose acetate.	1.2 – 1.4	Crystalline (less than cellulose); polyester blends have reasonably good mechanical properties; film is reasonably transparent; antistatic; moderate gas barrier.	Moisture sensitive (improved by blending with PCL); high water vapour permeability; low oil, solvent resistance; vulnerable to degradation during processing at high temperatures.	Soluble starch-PVOH loose fill; flushable backing film for sanitary products; agric. film and planters, single-use plastic bags; food packaging; slow release capsules; filler for tyres; molded items.	PP, PS, EPS for foamed peanuts; PUR for molded foams; LDPE, HDPE; recycled PE for lower grades.
PLA	PLA with various ratios of D- and L-isomer; blends with PCL, PHAs, starch polymers; blends with fibres.	1.25	Mechanical properties good; amorphous grades transparent; good water, oil, solvent resistance; moisture resistance reasonable (between starch polys and PET); good odour barrier; high heat seal strength; twist and deadfold; good UV resistance; polar thus easy to print.	Poor optical properties for crystalline grades; must be dried for processing; low Vicat temp;. low gas barrier (inferior to starch polymers); susceptible to hydrolysis at 60°C (followed by biodegradation).	Plastic cups and containers, wrappers, carpeting; blends (e.g. with PET) for textiles/ apparel; 'active' packaging for agric sheet; textiles for auto interiors, molded parts for E&E.	PE-HD & LD in food packaging; PET , PA (fibres); PP; Hi-PS (impact modified PLA);.
PTT	Pure; blends with PET/nylon	1.35	Crystalline; v good mechanical properties incl.: hard, strong and tough; excel. chemical resistance, excel. elastic recovery; lower processing temps than PET; easily dyed; faster crystallisation than PET	UV sensitive, practically not biodegradable.	High grade (low denier) fibres for apparel, carpeting; packaging films.	PET, PA, PP for fibres; PBT, PC for molding. Substit. Also possible for PLA, cellophane.
PBT	Compounded or alloyed form (e.g. with PC)	1.34	Similar to PET and particularly PTT but more highly crystalline, opaque, high impact strength; crystallises rapidly; excel. electrical properties; high continuous use temp.	UV sensitive, practically not biodegradable.	Molded electrical/ automotive parts; flame retardant compounds; possible fibres.	PC, PA, PET

Polymer	Main types (incl blends)	Density (g/cm^3)	Advantageous properties	Disadvantageous properties	Applications	Substitution on material / application basis
PBS	Blended with starch or adipate (to form PBS-A) copolymer .	1.26	Similar to PET; excel. mechanical properties and processability; hydro-biodegradable.	Fibre formation difficult; drying required	Mulch film, packaging, bags, flushable hygiene products; non-migrating plasticiser for PVC.	PET (in blends); PP
P(3HB)		1.25	Heat resistant; tough; ductile; good O2 barrier.	Highly crystalline thus opaque; stiff, brittle. Degrades at normal melt processing temp.	Nucleant or modifier	PS
P(3HB-co-3HV)		1.23-1.26	hardness	Stiff, brittle (less than P(3HB), yellows with age.		PS
(3HB-co-3HHx)		1.07-1.25	Good mechanical properties and processability	Crystallisation rate currently too slow for film blowing	Film (cast), non-woven paper and film coating;	HDPE to LLDPE; EVOH (for paper coating)
Cellulosics	Cellulose hydrate (cellophane); usually coated with nitrocellulose wax or poly(vinylidene chloride). Regen. cellulose; derivatives incl. cellulose acetate (CA), usually with DS>2.		Highly crystalline; fibrous, insoluble; good mechanical properties; good gas barrier at low rel. humidity; cellophane biodegradable.	Moisture sensitive (improved by coating); requires more aggressive processing conditions than starch; not thermoplastic (thus not heat sealable); need >25% plasticiser for thermoplastic processing; cellulose acetate only biodeg. with DS <1.7.	Coated cellophane films; viscose, lyocell and other regen cellulose fibres	

Appendix 2.5: Key properties and applications of petrochemical-based polymers

Polymer	Specific gravity (g/cm^3)	Properties	Applications
PETCHEM			
PVC	1.30-1.35	Low cost, versatile. Low crystallinity: good mechanical properties, particularly stiffness at low wall thickness, high melt viscosity at relatively low molecular mass, ability to maintain good mechanical properties even when highly plasticized.	Range of rigid, flexible and injection moulding formulations for building, agriculture, E&E (plumbing pipes, garden hose, shoe soles). Toxicity of vinyl chloride monomer during processing and as residual in PVC has led to its phasng-out in many applications.
PE-LD	0.92	Low cost commercial plastic. Mechanical properties poor above 50C. Poor aroma, flavour barrier. Subject to environmental stress cracking.	Packaging, houseware (garbage bag, rubbish bin, buckets).
PE-HD	0.96	Greater rigidity and better creep properties than PE-LD.	Structural applications, packaging of aggressive liquids such as bleach, detergent, and hydrocarbons. Also shopping bag, milk bottle.
PP	0.91	Chemical resistance same as PE but can be used to temperatures up to 120C	Building, E&E, packaging (molded automotive parts, potato crisp bags)
cc-PS	1.05	Hard, transparent materials with a high gloss. Below 100 °C PS molding materials solidify to give a glasslike material with adequate mechanical strength, good dielectric properties, and resistance toward a large number of chemicals for many areas of application. Above its softening point clear PS occurs as a melt which can be readily processed by techniques such as injection molding or extrusion.	Building & insulation, packaging (industrial and food),. Technical items include radio and television housings, video cassettes, electrical articles, computer accessories, and sanitary ware.
PMMA	1.17-1.20	Clarity, transparency, weatherability	Limited range: moldings for optical applications such as covers for car lights and illuminated signs.
PA6 (nylon6)	1.14	Abrasion resistance, fibrous, crystalline. Poor flavour barrier. Resistant to many organic solvents but attacked by phenols, strong oxidising agents and mineral acids.	Diverse applications in appliances, business equipment, consumer products, electrical/electronic devices, furniture, hardware, machinery, packaging, and transportation.
PET	1.37	Good mpact, heat resistance. Poor water barrier.	Fibres, packaging (softdrink bottle, textiles)
PBT	1.3	Highly crystalline	E&E
PC	1.20	(Relatively) high-temperature plastic – can be used up to 150C. Good toughness, transparency.	
POM	1.42	Good abrasion resistance. Excellent resistance to most organic solvents.	Moving parts
PUR foam	1.1-1.5	Flexibile; high elongation; high strength.	Packaging, prototyping; mattresses.
HI-PS	1.04-1.07	v. tough	Yoghurt cup, plastic cutlery, coat hanger, VCR box.
ABS-GP	1.05-1.07	Good resistance to non-oxidising and weak acids. Verytough	

Appendix 3: Summary overview of LCA data for bio-based and petrochemical polymers

Part 1: Summary of key indicators for primary plastics (pellets) from the LCA studies reviewed (state-of-the-art technologies only)

Type of plastic	Functional unit	Cradle-to-gate non-renewable energy use[1] [MJ/functional unit]	Type of waste treatment assumed for calculation of emissions	GHG emissions [kgCO_2eq./ functional unit]	Ozone precursors [g ethylene eq.]	Acidifi- cation [g SO_2 eq.]	Eutrophi- cation [g PO_4 eq.]	Reference
Petrochemical polymers								
HDPE	1kg	80	Incineration	4.84[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
LLDPE	1kg	72.3	Incineration	4.54[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
LDPE	1kg	80.6	Incineration	5.04[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
LDPE	1kg	91.7	80% incin.+ 20% landfilling	5.20[2]	13.0	17.4	1.1	Dinkel et al., 1996
Nylon 6	1kg	120	Incineration	7.64[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
PET (bottle grade)	1kg	77	Incineration	4.93[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
PS (general purpose)	1kg	87	Incineration	5.98[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
EPS	1kg	84	Incineration	5.88[2]	n/a	n/a	n/a	Boustead, 1999; own calc.
EPS	1kg	88	none (cradle-to-factory gate)	2.80	43.0	170.0	5.8	Estermann et al., 2000
EPS (PS + 2%SBR + Pentane + Butane)	1 kg	87	none (cradle-to-factory gate)	2.72	1.2	18.5	1.5	Würdinger et al., 2001
Bio-based plastics (pellets)								
TPS	1kg	25.4	Incineration	1.14	n/a	n/a	n/a	Patel et al., 1999
TPS	1kg	25.5	80% incin.+ 20% compost.	1.20	4.7	10.9	4.7	Dinkel et al., 1996
TPS	1kg	25.4	100% composting	1.14	5.0	10.6	4.7	Dinkel et al., 1996
TPS (maize starch+5.4%maize grit+12.7%PVOH)	1 kg	18.9	none (cradle-to-factory gate) [3]	1.10 [3]	0.2	4.6	0.5	Würdinger et al., 2001
TPS + 15% PVOH	1kg	24.9	Incineration	1.73	n/a	n/a	n/a	Patel et al., 1999
TPS + 52.5% PCL	1kg	48.3	Incineration	3.36	n/a	n/a	n/a	Patel et al., 1999
TPS + 60% PCL	1kg	52.3	Incineration	3.60	n/a	n/a	n/a	Patel et al., 1999
Starch polymer foam[4]	1kg	32.4	Composting	0.89	5.5	20.8	2.8	Estermann et al., 2000
Starch polymer foam[4]	1kg	36.5	Waste water treatment plant	1.43	5.8	20.7	3.1	Estermann et al., 2000
Starch polyester films	1kg	53.5	Composting	1.21	5.3	10.4	1.1	Estermann, 1998
PLA	1kg	54	Incineration [3]	3.45 [3]	n/a	n/a	n/a	Vink, 2002
PHA by fermentation	1kg	81	n/a	n/a	n/a	n/a	n/a	Gerngross and Slater, 2000
PHB, various processes	1kg	66 - 573	n/a	n/a	n/a	n/a	n/a	Heyde, 1998

[1] Total of process energy and feedstock energy. Non-renewable energy only, i.e. total of fossil and nuclear energy. In the "cradle-to factory gate" concept the downstream system boundary coincides with the output of the polymer or the end product. Hence, no credits are ascribed to valuable by-products from waste management (steam, electricity, secondary materials).

[2] Only CO_2. Embodied carbon: 3.14 kg CO_2/kg PE, 2.34 kg CO_2/kg nylon 6, 2.29 kg CO_2/t PET, 3.38 kg CO_2/t PS, 2.32 kg CO_2/t PCL, 2.00 kg CO_2/t PVOH.

[3] No credit for carbon uptake by plants.

[4] Materials manufactured from starch polymers using water as the blowing agent as substitute for synthetic foam (PS, PE, PU).

Part 2: Summary of LCA key indicators for end products (some of the products listed are commercialised, others not; see text)

Type of plastic	Functional unit	Cradle-to-gate non-renewable energy use*) [MJ/functional unit]	Type of waste treatment assumed for calculation of emissions	GHG emissions [kgCO_2eq./ functional unit]	Ozone precursors [g ethylene eq.]	Acidifi- cation [g SO_2 eq.]	Eutrophi- cation [g PO_4 eq.]	Reference
Foam (loose fills)								
Starch foam	1 m^3 (10 kg)	492	Waste water treatment plant	21.0	115	276	39.0	Estermann et al., 2000
Starch foam	1 m^3 (12 kg)	277	30% incin., 70% landfilling	33.5	10	83	9.9	Würdinger et al., 2001
PS foam	1 m^3 (4.5 kg)	680	Incineration	56.0	1200	325	42.0	Estermann et al., 2000
PS foam	1 m^3 (4 kg)	453	30% incin., 70% landfilling	22.5	57	85	8.0	Würdinger et al., 2001
PS foam (by recycling of PS waste)	1 m^3 (4 kg)	361	30% incin., 70% landfilling	18.6	55	107	9.9	Würdinger et al., 2001
Mater-Bi starch loose fills	1 kg	49		2	12	28	4	Estermann et al., 2000
FloPak starch loose fill	1 kg	23		3	1	7	1	Würdinger et al., 2001
EPS loose fill	1 kg	151		12	267	72	9	Estermann et al., 2000
FloPak EPS loose fill	1 kg	113		6	14	21	2	Würdinger et al., 2001
EPS loose fill (by recycling of PS wast	1 kg	90		5	14	27	2	Würdinger et al., 2001
Films and bags								
TPS film	100 m^2, 150 μm $^{2)}$	649	80% incin.+ 20% landfilling	25.30	100	239	103.0	Dinkel et al., 1996
Starch polyester film	100 m^2, 20 μm $^{2)}$	133	Composting	2.98	14.0	26.5	2.8	Estermann/Schwarzwälder, 1998
PE film	100 m^2, 150 μm $^{2)}$	1340	80% incin.+ 20% landfilling	66.70	180	238	15.0	Dinkel et al., 1996

*) Total of process energy and feedstock energy. Non-renewable energy only, i.e. total of fossil and nuclear energy. In the "cradle-to factory gate" concept the downstream system boundary coincides with the output of the polymer or the end product. Hence, no credits are ascribed to valuable by-products from waste management (steam, electricity, secondary materials).

Appendix 4: Polymers – Proposed policies & measures and estimates of their potential for GHG emission reduction (ECCP, 2001)

Specific Objectives	Proposed Measures	Possible Results	CO_2 savings potential (kt)	Comments
Making bio-degradability and non toxicity relevant to the consumers	• Avoid any delay in the implementation of the directive to reduce the concentration of biodegradable waste in landfills. • Subsidise the use of high quality compost • Improve infrastructure for separate collection and treatment of biodegradable materials (especially polymers) • Adapt composting Directive (biological treatment of biowaste; draft status) • Adapt packaging Directive: include compostable packaging	• Increase attention for appropriate treatment of organic waste • Improve and strengthen infrastructures for high quality compost and promote CO_2 savings • Products like compostable packaging can be recovered by composting (basic pre-requisite) • Compostable polymer products, e.g. packaging should get access to a cost effective recovery/waste system		• Clear objectives for the member states • Standards on high quality compost to be made available. • Market prediction for polymers is directly depending on waste infrastructure – we expect an EU – market share of 1-3Mt for compostable polymers • Compostability of products has to be proven by standards (DIN V54900, EN13432, UNI …), certification and labelling necessary >1000 kt (most of polymer products concerned) **up to 10000kt primary CO_2 savings**
Improve scope for application as well as technical and economic performance	• Promote basic research on RRM • Support demonstrative projects besides applied research	• More R&D stimulated • Easier decision for major investments		• Support advanced product lines, packaging, agricultural products, biowaste bags, carrier bags, catering…

Specific Objectives	**Proposed Measures**	**Possible Results**	**CO_2 savings potential (kt)**	**Comments**
Facilitate market introduction of RRM products	• VAT reduced (i.e. 4% off VAT rates) in case of materials based on renewable resources in specific applications (compostable packaging, catering; mulch films and other agricultural products, biotyres using biofillers, fibres) • Promotion of biodegradable materials with proven environmental benefits: • Example: (bags for the separate collection of organic waste, cotton buds and other hygienic products etc.)	• 10%market share EU (>1Mt biodegradable polymers) • Improve compost quality and avoid visual pollution. (0.1Mlt biodegradable polymers)	**>3500**	• Market is very big in size, starting with shopping bags and food packaging (fruits, eco-products) and mulch films • Avoid significant social and environmental costs related to specific applications of limited volume • **CO_2 savings based on secondary effects could be much higher**
Stimulate demand and consumer awareness (also on environmental benefits) for products based on RRM	• Public procurement favouring products partly or fully based on renewable raw materials • Information campaigns: explain advantages and recovery aspects to consumers/industries • Promotion of methodologies on assessment of env. impact of RRM	• Facilitate an economy of scale for producers • More interest for users/ consumers • More reliable data on the environmental impact of RRM versus non-renewable materials	**>500**	• Especially: biowaste bags, catering • Need for data of LCA for comparative analysis on specific sectors
TOTAL			**> 4000**	Primary savings

Appendix 5: U.S. policy on bio-based products

In the United States, bio-based products have been promoted by means of a pro-active technology policy for several years. Even though the U.S. policy in general jointly addresses bio-based materials and bioenergy, the steps taken are nevertheless very instructive and may help European policy makers when developing further suitable boundary conditions for bio-based products. This appendix is identical with the chapter "Policy framework: U.S. technology policy on biobased products" of an M.Sc. thesis prepared by Mr. Ludo R. Andringa at Utrecht University and The University of Oklahoma. The chapter is being reprinted here with kind permission of the author. The full reference of the M.Sc. thesis is: **L. R. Andringa: Analysis of technology policy and systems of innovation approach: the case of biopolymers in the United States. Utrecht University and The University of Oklahoma, February 2004** (available from the Department of Science and Innovation Management at Utrecht University).

A5.1 Biomass R&D Act

In August 1999 President Clinton's Executive Order (EO) 13134 was released. It was titled 'Developing and Promoting Biobased Products and Bioenergy' and called for coordination of Federal activities and efforts to accelerate the development of 21st century biobased industries. That President Clinton was serious is reflected by his declaration, in an accompanying Executive Memorandum, of a goal for the United States to triple the national use of biobased products and bioenergy by 2010. The EO directly resulted in an evaluation by the departments of Energy and Agriculture (DOE and USDA) of all current Federal activities related to biobased products and bioenergy. This evaluation formed the basis for a renewed, integrated and coordinated Federal approach to biobased products and bioenergy. Within a few months DOE and USDA reported on the evaluation and new approach in the Report to the President on Executive Order 13134 (released February 2000). In May 2000 the U.S. Congress (i.e., the Senate and the House of Representatives) passed the Agricultural Risk Protection Act of 2000 (H.R. 2559), which included the Biomass R&D Act of 2000. When President Clinton signed H.R. 2559 on June 20, 2000 it became a Public Law (P.L. 106-224) and EO 13134 was effectively replaced. Although before there had previously been some efforts to support biobased products, it was not until the passing and signing of the Biomass R&D Act (further referred to as Act) that the U.S. Congress officially and seriously recognized 'biobased industrial products' and included it in legislation, finding that converting biomass into biobased industrial products offers "outstanding potential for benefit to the national interest." [Biomass R&D Board 2001] [U.S. DOE and USDA 2000] [Walden 2001]

Section 1 of the EO 13134 illustrates the motivation (i.e. aspects of national interest) behind the Act. Four main reasons can be identified:

1. Create new economic opportunities for rural development (employment opportunities and new businesses).
2. Potential to protect and enhance our environment (improved air quality, improved water quality, flood control, decreased erosion, contribution to minimizing net production of greenhouse gases).
3. Strengthen U.S. energy and economic security (reduced U.S. dependence on oil imports, new markets and value-added business opportunities).
4. Provide improved products to consumers (new products).

[Biomass R&D Board 2001] [U.S. DOE and USDA 2000]

A5.2 Biomass R&D Initiative

The signing of the Act directly resulted in the establishment of a Biomass R&D Initiative (further referred to as Initiative) that represents the renewed, integrated and coordinated Federal approach to biobased products and bioenergy as designed by DOE and USDA. The Initiative is designed to be "the multi-agency effort to coordinate and accelerate all Federal biobased products and bioenergy research and development". The National Biomass Coordination Office (further referred to as Coordination Office) actually manages the Initiative. The Biomass R&D Board (further referred to as Board) and the Biomass R&D Technical Advisory Committee (further referred to as Committee) both coordinate the Initiative by providing guidance. The signing of the Act also authorized annual funding to USDA from 2000 through the end of 2005. [National Biomass Coordination Office 2003a] [Walden 2001]

The purpose of the Coordination Office, as indicated in Section 6 of EO 13134, is to ensure effective day-to-day coordination of activities under the Initiative, including those of the Board and the Committee. The Coordination Office serves as the executive secretariat of the Board and supports the work of the Board (e.g. by preparing reports). The Coordination Office also responds to the recommendations of the Committee. The Coordination Office does all this work to ensure effective implementation of the Act. [National Biomass Coordination Office 2003a] [Office of the Press Secretary 1999] [Walden 2001]

In July 2001 the Coordination Office published a draft vision and a draft roadmap on biobased products and bioenergy. The vision discusses the targets set by industry leaders. The goal of the roadmap is to develop an overarching and executive-level plan for an integrated bioenergy and biobased products industry and outline a strategy for achieving the targets set in the vision. With the roadmap the Coordination Office attempts to complement the more targeted roadmaps that already have been or will be published. The roadmap distinguishes and discusses issues for four interrelated areas: plant science, feedstock production, processing and conversion, and product uses and distribution. [National Biomass Coordination Office 2001g] [National Biomass Coordination Office 2001h]

The mission of the Board is to coordinate Federal efforts (e.g. programs), including planning, funding, and R&D, for the purpose of promoting the use of biobased industrial products. As indicated in Section 2 of EO 13134 the Board is co-chaired by the USDA Undersecretary for Research, Education and Economics and the DOE Assistant Secretary for Energy Efficiency and Renewable Energy. [Biomass R&D Board 2001] [National Biomass Coordination Office 2003a] [National Biomass Coordination Office 2003d]

The Board is directed by the EO 13134 to develop a biomass research program focused on "research, development, and private sector incentives to stimulate the creation and early adoption of technologies needed to make biobased products and bioenergy cost-competitive in national and international markets." In January 2001 this resulted in the release a strategic plan entitled 'Fostering the Bioeconomic Revolution in Biobased Products and Bioenergy'. This interagency strategic plan was released as instructed by the U.S. Congress in P.L. 106-224. The strategic plan is in fact a high-level summary of the emerging national strategy and can be seen as the first integrated approach to biobased products and bioenergy policies and procedures. It includes not only technology goals, but market and public policy goals as well. The inclusion of the last two expands beyond what was required by the legislation. These goals include the quantitative targets to reduce costs of technologies for integrated supply, conversion, manufacturing, and application systems for biobased products and bioenergy two- to ten-fold by 2010 and to increase Federal government purchases (or production) of bioenergy to 5% and relevant biobased products purchases to 10% by 2010. [Biomass R&D Board 2001] [Duncan 2001]

Under Section 3 of EO 13134 the Committee is directed to provide guidance on the technical focus of the Initiative to the Board and Coordination Office. The Committee consists of a group of 31 individuals from industry, academia, non-profits, agricultural and forestry sectors, who are experts in their respective fields. Amongst these experts are representatives from DuPont, Cargill and Cargill Dow. [National Biomass Coordination Office 2003a] [National Biomass Coordination Office 2003d] [Office of the Press Secretary 1999]

In January 2002 the Committee submitted recommendations on funding for Fiscal Year (FY) 2002, which the DOE's Office of Energy Efficiency and Renewable Energy (EERE) is supposed to incorporate into its biomass R&D program. After identifying crucial challenges different recommendations have been formulated for biofuels, biopower and biobased products, as well as cross-cutting recommendations. The Committee focused in its recommendations beyond R&D and further identified non-R&D priorities such as education and outreach activities. [Biomass R&D Technical Advisory Committee 2001] [National Biomass Coordination Office 2002a]

In October 2002 the Committee released a vision and roadmap for 'Bioenergy and Biobased Products in the United States' at the request of USDA and DOE. Both documents are intended for assisting in biomass-related research planning and program evaluation, which is one of the official functions of the Committee. The goal of the roadmap is to map the required R&D and identify public policy measures "for promoting and developing environmentally desirable biobased fuels, power and products". The roadmap distinguishes three categories in which research is required: feedstock production, processing and conversion, product uses and distribution. By August 2003 the Committee had completed a review of FY 2003 research portfolios of USDA and DOE. This review was based on the Committee's roadmap. [Biomass R&D Technical Advisory Committee 2002a] [National Biomass Coordination Office 2002e] [National Biomass Coordination Office 2003b] [National Biomass Coordination Office 2003f]

A5.3 Title IX of the Farm Security and Rural Development Act of 2002

Title IX of the Farm Security and Rural Development Act of 2002 (H.R. 2646/P.L. 107-171 or better know as the 2002 Farm Bill) reauthorized the Biomass R&D Act (extends it until 2007) in May 2002. In addition it provides USDA with $75 million of mandatory (non-discretionary) funding for the Biomass R&D Initiative and authorizes an additional $49 million annually in R&D funds for FY 2003 until FY 2007 subject to appropriation. Before this Farm Bill efforts relating to the Initiative had been funded through existing USDA and DOE authority. [Ames 2002] [National Biomass Coordination Office 2001a]

Section 9002 of Title IX of the 2002 Farm Bill gave a new direction to Federal procurement. It extended the Executive Order 13101, which already required Federal procurement of recycled and environmentally preferred products, and made the suggested voluntary purchasing of biobased products mandatory. The U.S. government is the world’s largest purchaser of goods (spending more than $275 billion annually, which represents about 20% of the Gross Domestic Product) and by having Federal agencies develop preferential purchasing programs (by 2005) Section 9002 of Title IX of the 2002 Farm Bill attempts to use some of this purchasing power to promote biobased products. Under Section 9002 USDA is directed to develop an approved list of biobased products for Federal procurement which it is expected to complete in 2004. This will be done in consultation with the Environmental Protection Agency (EPA), General Services Administration and the National Institute of Standards and Technology (NIST) of the Department of Commerce (DOC). The American Society for Testing and Materials (ASTM) will work with USDA to develop a minimum biobased content standard for biobased products on the list. Existing NIST standards will be used for testing environmental performance of biobased products. NIST has already developed a life cycle assessment software tool called BEES ("Building for Environmental and Economic Sustainability") that allows comparison of environmental and economic costs of competing building materials. Iowa State University has been asked to develop the actual biobased product testing in cooperation with USDA's Office of Energy Policy and New Uses. USDA has also been directed to establish a voluntary labeling program, similar to the Energy Star program (www.energystar.gov). Almost all these developments are still underway. USDA's Office of General Council is at this time reviewing a draft regulation that will include some of the first results of these developments (e.g. list structure). USDA received $1 million in funding in FY 2002 and in FY 2003 from the Commodity Credit Corporation (CCC) to support this effort and is likely to continue receiving this each year until FY 2007. [Ames 2002] [Darr 2003] [EPA 2001] [EPA 2003] [Mesaros 2003] [National Biomass Coordination Office 2003e]

A5.4 Initiative member departments and agencies

Seven departments and agencies have actively been involved in the Initiative: DOE, USDA, EPA, National Science Foundation (NSF), Department of Interior (DOI), Office of Science and Technology Policy (OSTP), and Office of the Federal Environmental Executive (OFEE). In addition to these seven departments and agencies the Initiative designates to participating non-member agencies a less active role. These include DOC, Office of Management and Budget and Tennessee Valley Authority. [National Biomass Coordination Office 2003a]

USDA was the first U.S. department to focus on biobased products through the formation of national research laboratories (1930s). In the 1990s USDA’s efforts relating to biobased products advanced to a new level with an appropriation of at least $50 million annually for research on new non-food uses for traditional food commodities (e.g. wheat, corn, soybeans). The year the Initiative was formed USDA received approximately $72 million (FY 2000) for the development, demonstration, commercialization, analysis, outreach, and education activities for biobased products and bioenergy. For FY 2003 USDA requested around $259 million for biomass related activities. [National Biomass Coordination Office 2001a] [National Biomass Coordination Office 2003d] [U.S. DOE and USDA 2000]

DOE directed its focus on bioenergy technologies as a result of the energy crisis (1970s). Since then DOE's biomass related activities have been effectively spearheaded by EERE. DOE received around $125 million at the start of the Initiative (FY 2000) for the development, demonstration, commercialization, analysis, outreach, and education activities for biobased products and bioenergy. In July 2002 DOE reorganized its EERE programs and integrated its biomass program to better meet with Act and recommendations of the Committee. The new biomass program will focus on developing R&D in the areas of gasification, cellulosic ethanol, and biobased products. Its mission is to improve biorefinery technologies to make biorefineries that are economical and sustainable. The R&D conducted in the biobased products area also addresses biobased plastics. Competitive solicitations will play a major role in accomplishing this mission. The FY 2003 budget for the Biomass Program totals to approximately $114 million. [National Biomass Coordination Office 2001a] [National Biomass Coordination Office 2002d] [National Biomass Coordination Office 2003d] [U.S. DOE and USDA 2000]

NSF funds research and education in science and engineering as an independent agency. NSF funds several biomass program areas such as metabolic engineering, biotechnology, plant biology, and genomics. Its FY 2003 budget for biomass related activities represents around $50 million. [Hamilton 2003] [National Biomass Coordination Office 2001c] [National Biomass Coordination Office 2003d]

The DOI and the three other Initiative member agencies do not conduct biomass R&D, but work to advance biomass R&D through policies, programs, and regulations. DOI supports forest and woodland management programs to offer biomass feedstock opportunities for the biobased industries. The EPA mainly provides guidance, tools, and information to assist agencies with implementing their Environmentally Preferable Purchasing Program by 2005. Additional roles include its environmental regulation and valuing biobased products in terms of environmental cost and benefits. OSTP advises the President and members within the Executive Office on the impacts of (biomass) science and technology on domestic affairs. The activities of White House's OFEE focus on the Federal community where it advocates, coordinates, and assists environmental efforts in areas such as waste prevention, recycling, procurement, and the acquisition of recycled and environmentally preferable products and services. The OFEE's connection to biomass is based on its responsibilities regarding green purchasing of biobased products. [Culp 2003] [EPA 2001] [National Biomass Coordination Office 2001b] [National Biomass Coordination Office 2001d] [National Biomass Coordination Office 2003d] [Pultier 2003] [Whitney 2003] [Winters 2003]

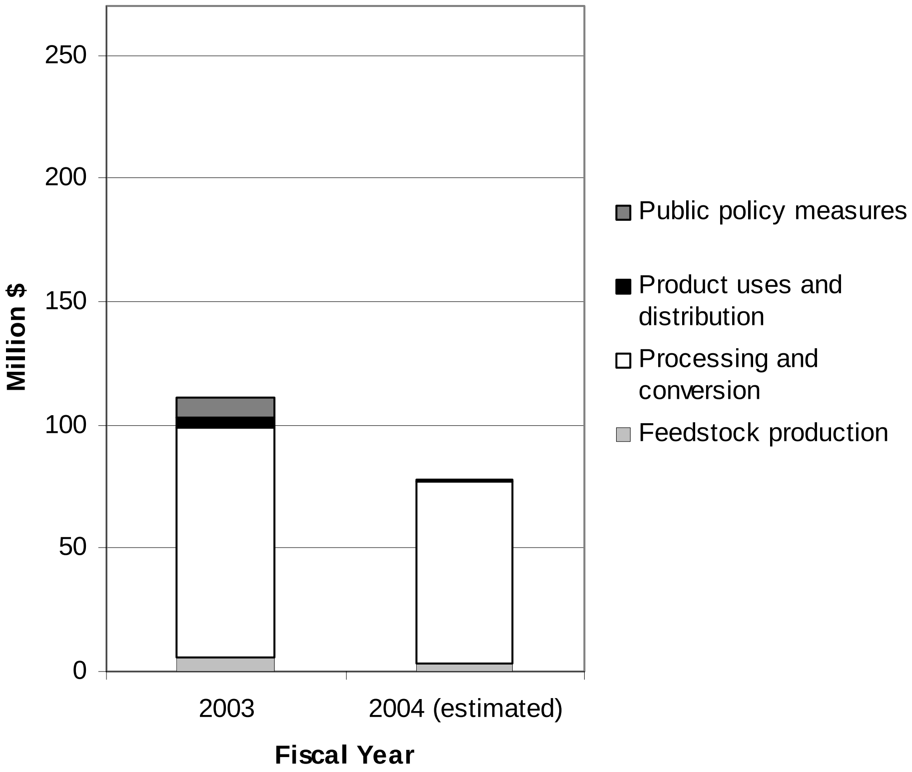
A5.5 Research portfolios and budgets of DOE and USDA

In February 2003 the Committee and Board met for the first time to discuss the progress and direction of the biomass related R&D programs and policy of the Federal government. Each of the seven member departments and agencies had prepared a summary of its biomass related activities. DOE and USDA have the most agencies involved in the forming and executing of technology policy related to biobased products and they also receive the largest budgets for these efforts. Based on this meeting of the Committee and Board and the Committee's research portfolio review for FY 2003 an overview will be provided on the direction and coverage of the main R&D areas by DOE and USDA. Figures A5-1 and A5-2 illustrate the budget allocations for DOE and USDA. Note that all FY 2004 budgets represent estimates. [National Biomass Coordination Office 2003d]

A5.5.1 Feedstock production

The Office of the Biomass Program (OBP) funds the R&D on feedstock production, while the Office of Science funds the basic science aspects. OBP strives to accomplish improvements in the cost and quality of raw materials. The R&D activities in this area cover biotechnology and plant physiology and feedstock handling (infrastructure). USDA's funding in this area is mainly divided over the Agricultural Research Service (ARS), Forest Service (FS), and the Cooperative State Research Education and Extension Service (CSREES). Both DOE and USDA allocate around 3-5% of their budgets (FY 2003 and FY 2004) to this R&D area. [National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003] [USDA 2003]

Figure A5-1: Overview of DOE research portfolios and budgets

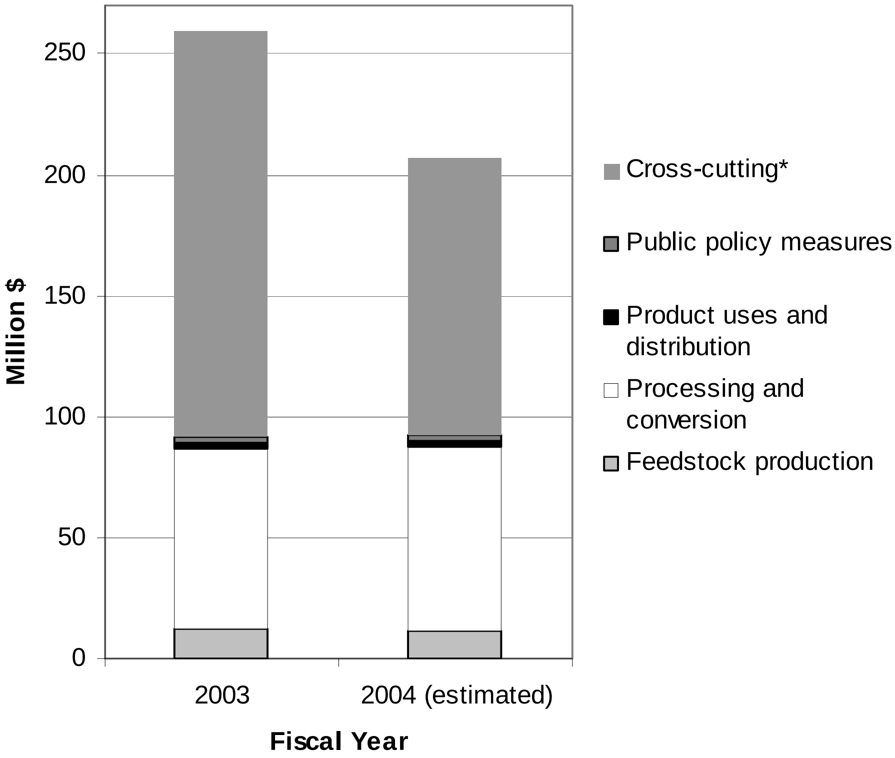


[National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003]

A5.5.2 Processing and conversion

Within this R&D area OBP's research focuses on bioconversion and thermo-chemical conversion (both receive similar amounts of funding). Thermo-chemical conversion mainly addresses the synthesis gas technologies. The bioconversion technologies are used for the production of fuels and chemicals from sugars. OBP's mission to improve biorefinery technologies is incorporated under bioconversion. Biorefinery integration receives almost 35% ($27.3 million) of DOE's total budget for FY 2004. USDA mainly funds the bioconversion area under ARS, FS, the Rural Development Program and USDA's Rural Business-Cooperative Service Grant Program (less than 1% of USDA's funding in this area has been focused on thermo-chemical conversion). R&D activities in this area include the projects funded by both USDA and DOE under the 2002 Integrated Biomass Solicitation and the 2003 Biomass Research and Development Initiative Solicitation. [National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003] [USDA 2003]

Figure A5-2: Biomass R&D Initiative



* Most of the funding in this area is allocated to CCC. The mission of the government-owned and operated CCC is to stabilize, support, and protect farm income and prices. USDA already had allocated around $100 million (FY 2000) to the CCC, but with the 2002 Farm Bill extending the program eligible producers of commercial fuel grade biofuels are reimbursed with FY 03 funding around $150 million (FY 04: $100 million). [National Biomass Coordination Office 2001a] [National Biomass Coordination Office 2001e] [U.S. DOE and USDA 2000]

[National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [USDA 2003]

A5.5.3 Product uses and distribution

Within this area OBP aims to overcome technical barriers that obstruct broader use of biobased products (including fuels and polymers). USDA's research in this area is conducted by ARS and FS for the development of high-value products, which mainly includes woody biomass and biodiesel from soybean oil. Both DOE and USDA allocate around 1-3% of their budgets (FY 2003 and FY 2004) to this R&D area. [National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003] [USDA 2003]

A5.5.4 Public policy measures to support biomass development

Public policy development does not receive R&D funding from USDA or DOE. However, both departments do fund efforts that contribute to the Committee's roadmap policy strategies. Efforts include analysis, support, education and incentives. OBP's funding in this area includes market and technical analysis of biomass technologies, state grants, Federal procurement of biobased products, education initiatives, and accelerating the Federal procurement of biobased products with USDA. Within this area DOE's Education Initiative received $3.9 million for FY 2003. For FY 2004 OBP will taken an estimated $4.0 million from all other R&D areas for analysis and corporate initiatives. USDA's Office of the Chief Economist also directed funding ($2.6 million for FY 2003 and FY 2004) to accelerating the Federal procurement of biobased products, as well as funding economic and market analysis and a biodiesel fuel education program. [National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003] [USDA 2003]

A5.6 Main focus of U.S. technology policy on biobased products

With the signing of the Act in 2000 the U.S. Federal government has refocused its technology policy. This is best illustrated by the six major policy documents that have been released since then by the Initiative. The technology policy described in these documents seems to be well coordinated and these documents show signs of effective integration of all Federal biomass related efforts. Another promising development is the signing and implementation of the 2002 Farm Bill. Not only did it reauthorize the Biomass R&D Act, but it also gives new direction to Federal procurement by making purchasing of biobased products mandatory. Although DOE and USDA budgets dedicated to biomass related activities have significantly increased since the forming of the Initiative, a sharp decline (-29% for DOE and -20% for USDA) can be noted from FY 2003 to FY 2004.

In terms of budget allocations, DOE and USDA can be considered as the major member departments within the Initiative. Their biomass related budgets are almost fully used for funding R&D. Approximately 39% of DOE's FY 2003 budget has been dedicated to Federal R&D performed by or in cooperation with national laboratories. The National Renewable Energy Laboratory (NREL) and National Energy Technology Laboratory receive most of this R&D funding (one-half and one-quarter respectively). USDA dedicated roughly 59% of its FY 2003 budget to in-house and intramural biomass related activities. From a historical perspective both departments have performed more than 90% of the biomass-related Federal R&D. [Biomass R&D Board 2001] [Bohlmann 2003] [National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003] [Paster 2003] [USDA 2003]

Since the forming of the Initiative, biomass related activities have been mainly focused on four R&D areas: feedstock production, processing and conversion, product uses and distribution, and public policy measures. Within the R&D areas the main focus is on processing and conversion (and its bioconversion sub-area in particular). When leaving the CCC then both DOE and USDA have currently (FY 2003 and FY 2004) dedicated more than half of their budgets to this R&D area. [National Biomass Coordination Office 2003d] [National Biomass Coordination Office 2003f] [Office of the Biomass Program 2003] [USDA 2003]

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