



Projections for the Production of Bulk Volume Bio-Based Polymers in Europe and Environmental Implications

M. K. Patel^{1,*} and M. Crank^{2,†}

¹Department of Science, Technology and Society (STS)/Copernicus Institute, Utrecht University, Heidelberglaan 2, NL-3584 CS Utrecht, Netherlands

²Department of Science, Technology and Society (STS), Utrecht University, Netherlands

In this paper we provide an overview of the most important emerging groups of bio-based polymers for bulk volume applications and we discuss market projections for these types of bio-based polymers in the EU, thereby distinguishing between three scenarios. Bio-based polymers are projected to reach a maximum of 1.75–3.0 million tonnes by 2020 in the EU-25 under very favourable conditions. While these are sizable quantities, they are modest compared to the expected production increase of 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. Energy and greenhouse gas (GHG) emission savings from bio-based polymers were found to be 20–50 GJ/t polymer and 1.0–4.0 t CO₂ eq/t polymer compared to petrochemical polymers. Bio-based polymers are thus very attractive in terms of specific energy use and emissions. 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. 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). The relatively low contributions compared to the total EU chemical industry are caused by the low production volumes of bio-based polymers compared to petrochemical polymers until 2020. While the growth rates of bio-based polymers are high, the low starting level entails that a longer time period is required until meaningful substitution levels are observed. Nevertheless bio-based polymers represent a worthwhile strategy by gradually reducing the environmental burden as a consequence of replacing fossil resources with bio-based resources. The developments outlined should be seen as the first steps towards a sustainable chemical sector.

Keywords: Bio-Based, Polymers, Market Projections, Energy, Greenhouse Gas Emissions, Land Use.

1. INTRODUCTION

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 many 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 (in the order of rising percentages, the production

shares are 1 weight-% aluminium, 4 wt-% glass, 7 wt-% plastics, 12 wt-% paper & board, 13 wt-% roundwood, 24 wt-% crude steel and 29 wt-% cement; no other bulk materials have been taken into account).⁴⁹

The fact that plastics are comparatively new to the market, with new applications being discovered at a higher rate than for other bulk materials^a 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. High growth is also projected

*Author to whom correspondence should be addressed.

†Present address: Environ Australia Pty Ltd, P.O. Box 560, North Sydney NSW 2060.

^aAs an example, the plastics content of an average European car increased from 2% by weight in 1965 to 8–10% by weight in the mid-1980s.⁵²

for the future: Plastics represent the fastest growing group of bulk materials and their growth rates may outpace GDP even until 2020 and may be only slightly lower in the period 2020–2030 (see e.g., Ref. [43]).

In view of the high and ever growing production of plastics, the substantial concomitant environmental impacts and—more recently—very high oil prices, the replacement of petrochemical plastics by bio-based plastics has been receiving increasing attention. Due to their use of renewable feedstocks, bio-based polymers are associated with savings of fossil fuels, biodegradability (depending on the product) and lower toxicity. Recent technological progress has also opened up new opportunities. At the same time, the early stage of technological development represents a challenge and so do the somewhat inferior thermal, physical and/or chemical properties of some bio-based polymers. Constraints on land availability and agricultural resource competition also weigh into the debate. Nevertheless several large chemical companies are making considerable efforts to develop, test and launch bio-based polymers which are targeted not only at niches but also at bulk applications (see Ref. [10]). Important activities are being undertaken by small and medium-sized enterprises (SME) in the areas of polymer production and processing. Policy is also increasingly addressing this novel area, with the goal of exploiting its possibilities.^b

Against this background it is the objective of this paper to investigate 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 conditions and environmental impacts. We limit ourselves to bio-based polymers that are already commercialized or which are very close to commercialization and which have the potential to be produced in bulk quantities. We exclude the large number of bio-based polymers which are in the research and development stage and are not yet produced at industrial scale; moreover, we exclude bio-based polymers which are targeted primarily at high value markets with low volumes, e.g., in the medical sector.

While most bio-based polymers are biodegradable, this is not a selection criterion for inclusion in this paper. The share of biogenous carbon in the product is also not a selection criterion. 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

^bIn the European Climate Change Programme in 2001 (Ref. [21]) EU policy addressed for the first time the use of renewable raw materials for the production of bio-based materials as a strategy to reduce greenhouse gas emissions. In the meantime various types of action (particularly R&D funding) have been taken at the EU level, in EU countries and especially in the U.S.

restriction could lead to more cost-effective solutions (greater environmental benefits at lower cost).

The scope of the assessment has been restricted by excluding blends of starch with non-degradable petrochemical polymers since these do not comply with current EU standards for compostability. Cellulosic polymers have been excluded because they have been losing market shares to petrochemical polymers in the last decades and because they would deserve a separate in-depth analysis. And finally, natural fibres and composites of natural fibres with petrochemical polymers are not covered by this paper since we refer here to polymeric materials only.

There are four principal ways to produce bio-based polymers, namely:

- (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);
- (iii) to produce bio-based polymers directly in genetically modified crops; or
- (iv) to gasify biomass and to produce monomers by applying C₁ chemistry.

We are not taking into account the fourth option because, to our knowledge, no investments have so far been made in this area. The third option is currently only relevant for polyhydroxyalkanoates (PHAs) and although commercialisation efforts are underway, bulk volume applications appear to be still many years off. This paper therefore focuses on the first two pathways of which the latter seems to be gaining importance.

The various polymer forms and production pathways introduced in this section will be discussed in more detail in Section 2.

The geographical scope of this paper is the extended European Union consisting of 25 countries. The time horizon of this prospective analysis is the year 2020. 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.

2. CHARACTERIZATION OF KEY BIO-BASED POLYMERS IN BULK CHEMICAL APPLICATIONS

In this section we briefly discuss the most important emerging groups of bio-based polymers (see Table I). 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, polylactic acid (PLA) has most likely already overtaken starch polymers due to NatureWorks' large-scale plant. Some of the other bio-based polymers, that are not yet manufactured commercially, are rather close to industrial production; e.g., polytrimethylene terephthalate (PTT) and PHAs. The bio-based polymers listed in Table I under the

Table I. Overview of currently most important groups and types of bio-based polymers.

Bio-based polymer or polymer group	Type of polymer	Production method
Starch polymers	Polysaccharides	Modified natural polymer
Poly(lactic acid) (PLA)	Polyester	Bio-based monomer (lactic acid) by fermentation, followed by polymerisation
Poly(trimethylene terephthalate) (PTT)	Polyester	Bio-based 1,3-propanediol by fermentation plus petrochemical terephthalic acid (or dimethyl terephthalate, DMT)
Poly(hydroxyalkanoates) (PHAs)	Polyester	Direct production of polymer by fermentation or in a crop (usually genetic engineering in both cases)
Other bio-based polymers		
— Poly(butylene terephthalate) (PBT)	Polyester	Bio-based 1,4-butanediol by fermentation plus petrochemical terephthalic acid (or DMT)
— Poly(butylene succinate) (PBS)	Polyester	Bio-based succinic acid by fermentation plus petrochemical terephthalic acid (or DMT)
— Polyurethanes (PURs)	Polyurethanes	Bio-based polyol by fermentation or chemical purification plus petrochemical isocyanate
— Nylon 6 (PA6)	Polyamide (PA)	Bio-based caprolactam by fermentation
— Nylon 66 (PA66)	Polyamide (PA)	Bio-based adipic acid by fermentation
— Nylon 69 (PA69)	Polyamide (PA)	Bio-based monomer obtained from a conventional chemical transformation from oleic acid via azelaic (di)acid

category "other" are either not (yet) produced commercially or serve niche markets and are produced only at very low levels. We will therefore not discuss them in Section 2 but we do include them as a combined product group in the subsequent analysis (Sections 3 to 5).

The polymers shown in Table I differ in their content of bio-based carbon. While starch polymers, PLA and PHAs are fully bio-based (but nevertheless fossil fuels are required for processing), only one of the two monomers forming PTT is produced from a renewable feedstock (PTT is not biodegradable; it has properties which make it comparable to high-performance polymers such as nylon in some respects). PHAs represent a special case since they can be either produced by fermentation or in a (genetically modified) crop, e.g., potatoes or miscanthus.

As shown in Table II, for the starch polymers, PLA, PTT and PHAs, there are a number of companies active in the area. In general they have low production capacities and are offering their products at prices which are still considerably higher than petrochemical polymers.

2.1. Starch Polymers

A starch polymer is a thermoplastic, biodegradable and incinerable material resulting from the processing of native starch by chemical, thermal and/or mechanical means.

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 and a highly branched polysaccharide—amylopectin. The level of amylopectin (typically 70%) varies between different starch types, as does the level of amylose. Currently, the predominant raw material for the production of starch polymers is corn, but other sources of starch such as wheat,

potato, tapioca and rice are also utilised depending on price and availability.

In 2002, about 30,000 tonnes of starch polymers were produced and the market share of these products was about 75–80% of the global market for bio-based polymers.¹⁶ Today, petrochemical co-polymers used for blending or complexing may constitute up to 50% of the total mass of the starch polymer product.³⁸ These co-polymers are generally derived from fossil feedstocks. Efforts are being made to substantially reduce the share of petrochemical co-polymers; one approach is to develop more effective chemical and biological starch modification processes,³⁸ the other is to make use of other bio-based compounds, such as Novamont's recently commercialized vegetable oil-based polyester Origo-BiTM which contains 30–70% renewable content.⁷

The dominant application area for Modified Starch Polymers is packaging (e.g., soluble films for industrial packaging, films for bags and sacks, and loose fill), amounting to 75% of the total market share for starch polymers. Applications in the agricultural sector include starch-polycaprolactone (PCL) blends for agricultural mulch film and planting pots. Further novel applications include materials for encapsulation and slow release of active agents such as agrochemicals.¹⁶ Since 2001, Goodyear has been using the starch Mater-Bi filler BioTRED in its GT3 tyre (sold on the Japanese market). Benefits include lower rolling resistance, noise reduction, reduced fuel consumption and CO₂ emissions, and reduced manufacturing energy requirements.³² There is very high potential for further growth of starch polymers in this application.

2.2. Poly(lactic Acid) (PLA)

PLA is an aliphatic polyester produced via polymerisation of the renewable fermentation product lactic acid.

Table II. Companies, production capacities and prices for selected large-scale bio-based polymers.^c

Producer	Region	Polymer type and trade name(s)	2003	2010	2003	2010	2003	2010
			Capacity (kt.p.a.) ^m EU-15	Capacity (kt.p.a.) EU-15	Capacity (kt.p.a.) Global	Capacity (kt.p.a.) Global	Price (/kg) Global	Price (/kg) Global
Starch polymers ^d			62	(200–250)	(77–200)	(200–300)	(€3.00) ^b	
Novamont, Italy	EU	Mater-Bi [®]	20 ^d	>20	35 ^{e, d}	>20	€1.50–€4.50 ^{e, f}	
Rodenburg, Netherlands	EU	Solanyl [®]	40 ^e	40	40 ^e	40	€1.00 ^e	
National Starch and Chem., U.S.	US	Ecofoam [®]			(20)	(>20)		
Chinese company	Asia	Thermoplastic starch			(100) ^{e, h}	(100)	€0.60 ^h	
BIOP, Germany	EU	BIOPar [®]	(10 in 2004) ⁱ	150 ⁱ	10 (~2004) ⁱ	150 ⁱ		
Biotec, Germany	EU	Bioplast [®] TPS	2 ^h		2 ^h			
Japan Corn Starch, Japan	Asia	EverCom [™]						
Nihon Shokuhin Kako, Japan	Asia	Placorn [®]						
Potatopak, Avebe, Earthshell		Baked starch derivatives						
Plantic	Australia							
Poly(lactic acid (PLA))			1	250–500	143.5	530–1150	(€3.00)	€1.50
NatureWorks, USA	US	Natureworks [®] (Mitsui Lacea [®] in Japan)		150–250 ⁱ	140 ⁱ	280–500 ⁱ	€2.20–€3.40 ^{i, j}	€1.35 ⁱ
Toyota, Japan	Asia	(Toyota Eco-Plastic)			50 (in 2004) ²	150–400 ⁱ		
Project in China	Asia	Conducted by Snamprogetti, Italy			2.5 (mid 2003) ³			
Poly(trimethylene terephthalate (PTT))						3–44	(€2.00–€5.00)	
Dupont	US	Poly(trimethylene terephthalate) PTT Sorona [®]			10 (in 2004) ^{4, k}	(41) ⁴	(€2.30)	
Polyhydroxy alkanates (PHAs)							€20.00 ⁵	(€2.00–€3.00)
PHA homopolymers								€2.20
Metabolix, U.S.	US	P(3HB), P(3HO)					€20.00 ⁵	€3.00–€5.00 ⁵
Biomer, Germany	EU	P(3HB)Biomer [®]	(0.05) ^l		(0.05) ^l			
Mitsubishi Gas, Japan	Asia	P(3HB) Biogreen [®]						
PHA copolymers					1.4	30–60	€10.00–€12.00	€2.50–€3.00
Metabolix, U.S.	US	P(3HB-co-3HV)			1.1 ^{6, m}	50 (in 2008)	(€10.00–€12.00) ⁷	€3.00–€5.00 ⁷
(in co-operation with ADM)		Biopol [®]						
PHB Industrial, Brazil	S.Am	P(3HB-co-3HV) ^e			0.05 ⁸	4 (in 2008) ⁹		

¹BIOP (2003); ²TMC (2003); ³ENI (2001); ⁴Genencor (2003); ⁵Biomer (2003); ⁶Metabolix (2003); ⁷Petersen et al. (1999); ⁸PHB IND (2003); ⁹Seameo Searca (2006).
^aIncludes blends with biodegradable synthetics such as PCL, PVOH. ^bNovamont prices assumed indicative of category as a whole. Average of Novamont range quoted here.
^cCapacity 2003 ~20 kt.p.a.; licensed production elsewhere (assumed outside EU) ~15 kt.p.a. ^dPers. comm. with Catia Bastioli of Novamont S.p.A., Novara, Italy. 15 May 2003. ^eLower price foams, upper price films & specialty, average price (weighted) is estimated to be in the range of €2.50–€3.00. ^fCapacity 2003 ~20 kt.p.a.; licensed production elsewhere (assumed outside EU) ~15 kt.p.a. ^gEstimate, could not be verified. ^hPers. comm. with Yoshiro Okino of Showa Highpolymer Co. Ltd., Tokyo, Japan. 3 December 2003. ⁱPers. comm. with Bob Springs of Cargill Dow Polymers LLC (now Natureworks L.L.C.), Naarden, the Netherlands. 3 June 2003. ^jLower price for large volume sales, upper price for samples/small quantities. ^kInitial capacity 10.8 kt.p.a.; capability to expand to 45 kt.p.a. ^lAssume typical scale-up is 20× pilot plant: take current production = est. pilot plant capacity. ^mBased on 50,000L fermentor, batch time 40 h, yield (assumed) 100 g/L. ⁿPers. comm. with Remy Jongboom, Jules Harings and Jaap van Heemst of Rodenburg Biopolymers, Oosterhout, the Netherlands. 27 May 2003. ^okt.p.a. = kilo tonnes per annum.

PLA is thermoplastic and biodegradable and it has good physical and mechanical properties, making it a candidate for substitution for petrochemical thermoplastics in certain application areas.

^cThis table is only for starch polymers, PLA, PTT and PHAs. For details on the other bio-based polymers given in Table I, see Ref. [15]. Note that due to the fast development of the bio-based polymer sector very recent developments may not be included.

Lactic acid can be produced by anaerobic fermentation of carbon substrates (e.g., glucose, lactose) with micro-organisms such as bacteria or certain fungi. The range of raw materials suitable for lactic acid fermentation includes sugars, molasses, sugar beet juice 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), thus leading to more abundant and cheaper feedstocks.

At the forefront of the development of PLA for bulk applications has been the U.S. company Cargill. Cargill first produced PLA on a semi-commercial scale in 1994. In 1997 they signed a joint collaboration agreement with Dow Chemical to explore commercialisation of PLA and market opportunities for PLA products. This was followed up in 2000 by the establishment of the joint venture Cargill Dow LLC. The joint venture brought a 140,000 tonnes per annum (t.p.a.) PLA plant on line in 2001, followed up by a 180,000 t.p.a. lactic acid plant in 2002 to supply the monomer, establishing PLA as the second type of bio-based polymers after starch polymers to be commercialised and produced on a large scale.¹¹ In 2004, the company name was changed to NatureWorks LLC when Dow Chemical decided to leave the joint venture and Cargill assumed 100% ownership. Alongside building up production capacity, NatureWorks has been developing the market for PLA by establishing supplier relationships and identifying new applications. While 70% of PLA produced today (value for 2003) is used in packaging, NatureWorks predicts that within the next 10 to 15 years there will be a major shift away from packaging and towards fibres and fabrics, transportation and electronics.¹¹

2.3. PTT from Bio-Based PDO

Polytrimethylene terephthalate (PTT) is a linear aromatic polyester produced by polycondensation of 1,3-propanediol (PDO or trimethylene glycol) with either purified terephthalic acid (PTA) or dimethyl terephthalate (DMT). While both these monomers—the diacid and the diol component—are conventionally derived from petrochemical feedstocks, DuPont, Tate & Lyle and Genencor developed a process for producing PDO using an aerobic bioprocess with glucose from corn starch as the feedstock.¹⁹

In the late 1960s, Shell attempted the commercialisation of (petrochemical) PTT but was unsuccessful due to the high cost of PDO produced via hydration of acrolein. Thus, while polyethylene terephthalate (PET) and polybutylene terephthalate (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 Shell found a more cost effective means of producing (petrochemical) PDO from ethylene oxide using newly developed catalysts. Commercialisation of PTT under the brand name Corterra[®] followed in 1999.⁴⁶ In 2004, the first world-scale PTT plant, with a capacity of 95,000 t.p.a., was brought on line in Montreal, Canada. The plant is operated by PTT PolyCanada, a 50/50 limited partnership of Shell Chemicals Canada Ltd and Investissements Petrochimie (2080) Inc., a subsidiary of SGF Chimie.⁴

In parallel to Shell's efforts to commercialise petrochemical PTT, DuPont introduced its own product from

PTT (also known as "3GT") with the brand name 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.³⁵ To obtain a foothold in the market DuPont also started with PDO production from petrochemicals. In March 2004, DuPont formed a joint venture with Tate & Lyle, Plc., a major corn-based products company with expertise in fermentation processes. The joint venture, DuPont Tate & Lyle BioProducts, is currently building a plant for the production of bio-based PDO. The plant will be located in Loudon, Tennessee and is scheduled to commence operation in the fourth quarter of 2006 with a capacity of 45,000 t.p.a. of BioPDO[®].²⁰

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 X-ray film, magnetic tape (audio, video and computer) metallized film, strapping and labels.⁴⁷

2.4. Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) constitute a class of bio-based polyesters with a wide variety of material properties. Like PLA, PHAs are aliphatic polyesters produced via fermentation of renewable feedstocks. Whereas PLA production is a two-stage process, comprising fermentation to the 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.

PHAs have a semicrystalline structure, the degree of crystallinity ranging from about 40% to around 80%¹ depending on the length of the side chain, which can vary from zero to 19 carbon atoms. Due to this structural diversity, certain PHAs exhibit the property set of rigid thermoplastics, others of thermoplastic elastomers, and others of materials useful in waxes, adhesives, and binders.³⁶

Feedstocks currently being utilised for PHA production include sucrose, vegetable oils and fatty acids. In theory any carbon source can be utilised, including lignocellulosics from agricultural by-products. In practice, as for other fermentation-based products, 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 lignocellulosics and other lower-value feedstocks.

In the early 1990s Zeneca UK produced the PHA Poly-3-hydroxybutylene-co-3-hydroxyvalene 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 kilogram (kg) with material from a planned 5,000 t.p.a. semi-commercial plant projected to decrease to US \$8–10 per kg—still a prohibitive price for bulk applications. In 1996, Zeneca sold its 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 P(3HB-co-3HV) under the trade name Biopol® by means of fermentation. In 1998, Monsanto ceased its PHA operations and in 2001 sold its Biopol® assets to the U.S. biotechnology company Metabolix.³⁶ Metabolix is currently pursuing PHA production both by fermentation and in genetically modified crops. For the production by fermentation, Metabolix has partnered with Archer Daniels Midland (ADM) to commercialise production. A PHA plant with a capacity of 50,000 t.p.a. is to be built by ADM adjacent to its wet corn mill in Clinton, Iowa in the USA, with construction scheduled for completion in mid-2008.³⁷

As for all bio-based polymers, producers of PHAs are not only looking at the 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.

3. MARKET PROJECTIONS FOR BIO-BASED POLYMERS

Projections of production volumes for bio-based polymers have been developed in this paper using the expectations of producers as a starting point. The effect of policies & measures (P&Ms) is also taken into account for two out of the three scenarios. P&M options include:

- Increased R&D for bio-based products and the related processes
- Harmonised standards, e.g., on composting
- Fiscal and monetary support such as direct subsidies and reduced VAT (value added tax) rates
- Inclusion of bio-based polymers in climate and product policy (e.g., by means of tradable credits in the EU greenhouse gas emission trading scheme),
- Adaptation of waste legislation and waste management (e.g., partial exemption from the German Green Dot system for packaging materials)
- Directives for a mandatory percentage of chemicals to be produced from biomass (by analogy with the biofuels directive).

Some of these P&M options are complementary while others are exclusive. A selection of which P&Ms might be adopted is beyond the scope of this paper so it is assumed

here that the P&M mix is adopted will favourably impact bio-based polymer production volumes.

It is acknowledged up front that we did not conduct a rigorous techno-economic analysis as a basis of our scenario projections. Such a rigorous analysis would have required detailed estimates of the production costs of all bio-based polymers and their petrochemical counterparts using very specific assumptions about the development of the total production of polymers, fossil fuel prices, biomass prices, the choice and effectiveness of individual P&Ms and several other parameters.⁴

The approach taken in preparing scenario projections involves the following three steps:

- (I) Producer 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) Information on the market demand by application area was compiled.
- (III) An attempt was then made to develop plausible time series for production in the EU that take into account supply and demand expectations and also the 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) in 2010: According to these estimates bio-based polymers are expected to grow in the European Union from 25,000 tonnes in 1998 to 500,000 tonnes in 2010 without supportive P&Ms and to 1 million tonnes with P&Ms.
- European Bioplastics (formerly: 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 in 2020 (Ref. [33]).⁵ Half of this total is expected to consist of compostable products while the other half is 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 tonnes are expected to be bio-based.⁹ 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

⁴In a simplified manner, this type of approach has been applied in our project BREW,¹⁰ which, however, exclusively focusses on the production of bio-based polymers by means of biotechnology.

⁵The total "biopolymer" market in the EU in 3–5 million tonnes, of which 70–80% are expected to be bio-based.

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 600,000 tonnes of bio-based polymers for the EU by 2010. This hence supports the estimate made by the ECCP (500,000 tonnes in 2010 without P&Ms and 1 million tonnes with P&Ms).

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 Ref. [15], Appendix 1), which was prepared to estimate the potential market for Nodax™, P&G's proprietary family of PHAs which has not yet been commercialised. The total amounts to 1.17 million t.p.a. worldwide in 2001–2002, of which the fast food industry accounts for 60%. Total food packaging represents around 1 million tonnes, 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 or PTT) and applications in the automotive and the electric/electronic sector have not been taken into account; moreover certain products that P&G are not interested in for Nodax™ such as loose-fill packaging material have been excluded. The market potential outside the food sector is substantial as, for example, NatureWorks' estimate for the PLA market in the fibre sector shows (50% of the total market). European Bioplastics 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)

and that there are also interesting markets in the area of durable products apart from fibres.

In Table III, 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 total polymer volumes (according to Step I). This yields a 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.

In Step III, time series for the growth of bio-based polymers in the EU until 2020 have been developed by taking into account supply and demand expectations and also unit size of large plants. Table IV shows two scenarios which are named "WITHOUT P&M" and "WITH P&M." The totals are closely linked to the ECCP estimates for 2010 (as reviewed in Step I) 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 1.

The *current* global market potential of least 2 million tonnes that was derived in Step II above from P&G's analysis is in agreement with the worldwide data for 2010 in Table IV. The EU market potential estimates according to Table III indicate that the estimates in Table IV for Europe by 2020 are plausible or possibly even underestimated. Also in comparison with European Bioplastics' expectation for 2020 (2–4 million tonnes for all bio-based) the EU values for 2020 in Table IV seem to be underestimated. It must be recalled here that this report is based

Table III. 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

¹Petrochemical and bio-based (bio-based nowadays less than 0.1%); split by application area according to APME. ²Purely accounting for growth of polymer production as a whole, without taking into account larger market potential shares due to technological progress and market development.

³Independent 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.

⁴Value for 2020 from the Clean Technologies project.⁴⁵

Table IV. Projections for the production of bio-based polymers, 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
EUROPE						
2002	25	25	0	0	25(<0.1%)	25(<0.1%)
2010	250	500	250	500	500(0.9%)	1000(1.7%)
2020	375	750	500	1,000	875(1.25%)	1750(2.5%)
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 represents shares of bio-based relative to petrochemical polymers relative to petrochemical polymers. According to the "Clean Technologies Project"²³ 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).

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 (not shown in Table IV). 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, PURs and PAs (see Table I)—or at least some of them—in the marketplace. In the HIGH GROWTH scenario the total production of bio-based polymers is estimated at 3 million tonnes by 2020.

It must be emphasized that the per-capita-production values differ substantially between bio-based and petrochemical polymers: Today 66 grams of bio-based polymers are produced per capita per annum, while the production

of petrochemical polymers is around 180 kg/(cap*a). The per-capita values for bio-based polymers by 2020 range between 2.3 kg/(cap*a) in the scenario "WITHOUT P&M" and 7.9 kg/(cap*a) in the "HIGH GROWTH" scenario. Compared to the use of petrochemical polymers (approx. 120 kg/(cap*a) in 2000) these seem to be reasonable (and "imaginable") quantities even in the HIGH GROWTH case provided that bio-based polymers make their way into products of everyday life.

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 discussion which focuses on the scenarios "WITHOUT P&M" and "WITH P&M," begins with bio-based polyesters, polyurethanes and polyamides, which are dealt with as a group, and continues with starch polymers.

3.1. Bio-Based Polyesters, Polyurethanes and Polyamides

Bio-based polyesters/PURs/PAs 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. NatureWorks' facility in Nebraska is an example for such a world-scale plant, with an annual production capacity of 140,000 t.p.a. Future unit sizes for large-scale plants may range between 100,000 t.p.a. to 200,000 t.p.a. and possibly even beyond this 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 IV can be attributed to a (rather limited) number of plants in the EU and worldwide. For the EU, the production volumes presented in Table IV in the scenario "WITH P&M" are equivalent to 4 plants in 2010 and to 8 plants in 2020.

3.2. 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 IV). An

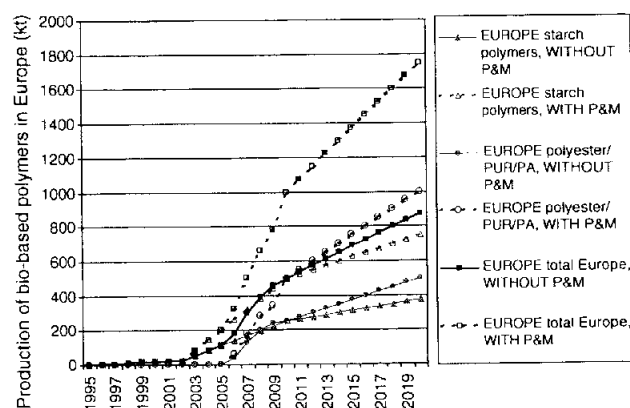


Fig. 1. Development of bio-based polymers in the EU until 2020—Scenarios "WITHOUT P&M" and "WITH P&M."

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 4,000 tonnes and 12,000 tonnes respectively. To our knowledge, the technology is modular in nature and therefore, only relatively small economies of scale can be expected.

Turning our attention to application areas, an insight is provided by the fact that despite the strong efforts and the commercial success of the starch polymer business over more than a decade, total production capacity remains limited to 30,000 t.p.a. in the EU for Modified Starch Polymers only and 70,000 t.p.a. when Partially Fermented Starch Polymers are included. This suggests that totally new applications are required in order to reach the overall quantities according to Table IV. The use of starch polymers as filler and partial substitute for carbon black in tyres is the only potential large-scale application that is known to us 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 statistics⁴⁹ 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%
- Share of carbon black that can be substituted by starch polymer fillers: 20% or 50%

This results in starch polymer outlets in the EU of

- 180,000 t.p.a. (range: 100,000–250,000 t.p.a.) for a substitution of 20%
- 450,000 t.p.a. (range: 250,000–600,000 t.p.a.) for a substitution of 50%.

Other aspects which have not been taken into account but which influence the production of starch polymer fillers in the EU include the volume of tyre production, imports and exports of fillers and the substitution of carbon black in (industrial) rubber products. The full exploitation of these substitution potentials is estimated to take around two decades provided that the technology and the products prove to be clearly advantageous. The comparison with the starch polymer projections for 2020 according to Table IV 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 clamshells). This has not been investigated since detailed market research is beyond the scope of this paper.

3.3. The “HIGH GROWTH” Scenario

While very little information is available on the market prospects of many types of bio-based polymers, a few considerations may help to put the assumptions made in the “HIGH GROWTH” Scenario into perspective:

- PTT, PBT, PBS, PURs and PAs (refer to Table I for full names and production methods) are nowadays 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 (PAs) 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 terms of energy savings or cost savings per unit product) could therefore mean a decisive advantage for its producer, allowing fast market introduction.
- The same argument holds for polyurethanes (PURs). Similar to PAs, PURs are mostly used in high-value application areas such as furniture, apparel and automobiles where the potential for substitution is relatively high.

3.4. Caveats

As explained earlier, the values presented in Table IV and in Figure 1 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 NatureWorks. NatureWorks serves as a valuable case study since other players producing new bio-based polymers could be expected to have 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 with the actual development; and
- gathering information from polymer processors about their experience.

While until early 2005 the demand and hence also production were understood to have been behind schedule, the conditions have drastically changed since the surge in the oil price, with demand for NatureWorks PLA now outstripping the supply. However, the rather early stage of development, limited capital availability for new investments and the unclear future about energy prices and polymer production in Europe act as obstacles preventing more dynamic development of the bio-based plastics sector.

As a consequence, our projections for the production of bio-based polymers (Table IV, Figure 1) may be too optimistic in terms of growth rates and final production volumes in 2020. On the other hand, in the case of sustained high oil prices, new actors may emerge in bio-based plastics production. High uncertainty regarding production volumes is obviously implicit in an emerging industry. This must be taken into account in the next sections of this paper (Sections 4 and 5).

4. ASSESSMENT OF THE ENVIRONMENTAL AND SOCIO-ECONOMIC EFFECTS OF BIO-BASED POLYMERS

The main purpose of this section 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 Section 3. The savings of fossil fuels, the effects on greenhouse gas emissions and the consequences for land use are studied.

One mass unit of polymer in primary form has been chosen in this study as the basis of comparison (functional unit). Ideally the analysis should be conducted on each end-use product (e.g., TV housing, toothpick packaging), but this is impracticable given the enormous number of products on the market and the difficulties that would arise when wanting to make a representative choice

In environmental life cycle assessment and energy analysis, typically two types of system boundaries, are distinguished:

- 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 paper.
- 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 paper, the use phase (including further processing to an end product and its use) is assumed to be comparable for the various types of polymers studied and is therefore omitted.

In this paper, we chose to conduct a cradle-to-grave analysis because the inclusion of waste management makes the assessment more complete compared to cradle-to-factory gate. As mode of disposal, we chose incineration without energy recovery. The contribution to global warming as a consequence of waste incineration can be expected to differ substantially for bio-based versus petrochemical polymers due to the different origin of the embodied carbon.

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 are kept confidential. Moreover, several impact categories are closely related to energy use (compare Ref. [30])—i.e., they are determined by the fuel type (e.g., coal vs. natural gas) and the technology of the combustion process (e.g., air preheat and flue gas scrubbing). Thirdly, different methodologies and indicators are in use for some impact categories (e.g., for toxicity), leading to contradictory results in some cases and making so-called single-score indicators (e.g., Ecoindicator 99) questionable. For these reasons, we decided to limit the impact categories covered in this paper to the most relevant independent parameters, namely energy use, GHG emissions and land use.

4.1. Input Data for the Environmental Analysis

In contrast to the wide interest in bio-based materials, the availability of relevant data for conducting comparative environmental assessments and the quality of these data is still quite limited. Some general findings in this respect are summarized as follows:

- For starch polymers, several studies have been prepared (e.g., Refs. [17, 51 and 23]). These address almost exclusively Modified Starch Polymers. Very little information is available on the use of starch polymers as fillers in tyres (only published as final results,¹⁴) and on Partially Fermented Starch Polymers (only available as a University of Utrecht 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 (with different types and shares of petrochemical co-polymers) and various waste management treatment options are assessed (for a comparative overview see also Ref. [39]). If exceptions related to malfunctioning and outdated technology are 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 GHG emissions.^f Due to the use of different methodologies the

^fResults for other impact categories are also available for natural fibre composites and for a thickener for a lacquer³⁹ but these products are outside the scope of this paper.

Table V. Specific energy use (non-renewable 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 ^a			1.0 ^a	Estimated for this study
PBS, long term			10 ^a			1.0 ^a	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"⁹, 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. ¹Non-renewable energy use according to cradle-to-grave analysis, without credits for energy recovery. ²Cradle-to-grave analysis. Assuming full oxidation without any credits. ³50% LLDPE + 50% HDPE according to Boustead (1999). ⁴Without petrochemical copolymers. ⁵Approximation: 20% pure starch polymers, 10% starch polymers with 15% petrochemical copolymers and 70% starch polymers with 52.5% petrochemical copolymers. ⁶Case 9 in Akiyama et al. (2003). ⁷Case 5 in Akiyama et al. (2003). ⁸Assumed to be equivalent to PTT long term. ⁹This group includes, apart from PUR and PA, all polyesters except for PLA, i.e., PHA, PTT, PBT, PBS, PBSA (and possibly others).

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 CO₂ emissions) has been prepared by NatureWorks.⁵⁰ Very simple analyses for PLA production from rye and whey have been conducted by the authors of this paper.
- For PTT, a preliminary analysis has been performed by the authors of this paper (see Ref. [15]); this analysis has shortcomings and needs to be analysed in more depth, which will most likely lead to lower estimates.¹⁰
- For PHA, several studies are available resulting in a wide range of energy use and CO₂ emissions. While the values at the higher end of the reported range are higher than those for petrochemical polymers, clear benefits also seem to be possible. The fact that PHA prices currently exceed those of other bio-based polymers is a consequence of the low yields and efficiencies. These drawbacks need to be overcome as a prerequisite for wide commercial success. If achieved, the environmental impacts of PHAs can be expected to be clearly lower compared to petrochemical bulk polymers.

The environmental assessment is based on data from published LCA studies and environmental analyses (for

details, see Ref. [15]). As a consequence, the results might not be fully comparable across the products in terms of the methodology used. Based on cross-comparisons, however, we expect the resulting inaccuracies to be limited.

For petrochemical polymers, the APME Ecoprofiles (PlastEurope) prepared by I. Boustead (1999–2003) represent a generally acknowledged database that has been used as a reference in most cases.^{g,h}

A particular challenge of this paper is the prospective nature of the environmental assessment. This means that technological progress needs to be taken into account since it generally contributes to reducing 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. This was not feasible in view of the information available. For

^aAn exception being in cases where there was no data available at the time; e.g., for petrochemical PBT.

^gAPME's Ecoprofiles refer to the system boundary cradle-to-factory gate, while we have chosen the system boundary cradle-to-grave without energy recovery (see above), namely waste incineration without energy recovery. Since this system does not offer advantages or disadvantages in terms of energy use or GHG emissions compared to the system "cradle-to-factory gate," the results are identical for the two systems.

this reason it was decided to take a simplified approach; the data on specific energy use, emissions and land use compiled in the tables discussed below (Tables V and VI) is hence considered valid for both foresight years, 2010 and 2020. For petrochemical processes no substantial technological progress was assumed due to the maturity of most of the technologies used.

The values printed in bold in Table V 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. The 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;³⁸ another option may be blending of diverse bio-based polymers which we have not studied. For PLA, the value for the long term refers to the biorefinery concept where lignocellulosic feedstocks

(corn stover) are used as a second source of fermentable sugars (in addition to starch) and energy is generated from the lignin fraction.

As discussed in Section 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 product shares of the other bio-based polymers because the related energy use and GHG emissions differ widely (see Table V). Since this information is not available, rough estimates have been made: To cover bio-based polymers that are *not* starch polymers, we distinguish two product categories, namely PLA and a mixed category "Other bio-based polyesters, PURs and PAs" (see last row of Table V). In line with the categorisation in Section 3 this group is intended to include, apart from PURs and PAs, 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 polyester while the "Other bio-based polyesters, PURs and PAs" are considered to be negligible. In the scenario "HIGH GROWTH," on the other hand, the total additional production beyond the scenario "WITH

Table VI. 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., 2002	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 2-0.5 corn + 0.5 stover	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
P(3HB), long term (ex glucose)						0.55
Category "Other bio-based polyesters, PUR and PA," ¹¹ long term						0.60

¹Without petrochemical copolymers. ²Potato (data for fresh matter, fm; for all other crops in this table dry matter, dm). ³Corn. ⁴High fermentation yield: applies to case 5 (and also case 6-8) in Akiyama et al. (2003). ⁵High fermentation yield: applies to case 9 in Akiyama et al. (2003). ⁶According to Akiyama et al., 2003. 1 kg of soybean oil from 5.4 kg of soybeans, Figure 1. PHA yield = 0.7 g/g, Table I. 95% PHA recovery, Table I. ⁷According to Akiyama et al., 2003. 1 kg of glucose from 1.46 kg of corn, Figure 2. PHA yield = 0.37 g/g, Table I. 95% PHA recovery, Table I. ⁸Average of range in Dornburg et al., 2004. ⁹Using same crop yields as for Cargill Dow case. ¹⁰Using same crop yields as for PLA-year 1 case. ¹¹This 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.

P&M" is assumed to belong to the category "Other bio-based polyesters, PURs and PAs."

The energy and emission savings resulting from bio-based polymers (see Table V) are high in comparison to the energy use of other bulk materials: Excluding the figure²⁷ for PHA by fermentation, the lower end of the range of energy savings attributed to bio-based polymers, i.e., 10–15 GJ/t, is on par with the total energy needed to make 2–3 tonnes of cement, 1–2 tonnes of secondary steel (electric arc steel) or recycled glass, about 1 tonne of paper/board or about 1/2 tonne of recycled aluminium. The high saving opportunities related to bio-based polymers are partly caused by the fact that petrochemical polymers are energy intensive to produce (on a mass basis); moreover, some of the processes covered in Table V account for future technological progress. This confirms the outcome of earlier publications according to which, *in specific terms* (e.g., per mass unit of polymer), bio-based polymers offer very substantial saving potentials (see Ref. [39]).

The LCA studies used contain information about the type and quantity of crop input (number of tonnes of crop required per tonne of polymer). Using average yields for crop production (compiled by Ref. [18]) specific land use has been calculated (see Table VI; the values printed in bold are used for further calculations). The estimate for the category "Other bio-based polyesters, PURs and PAs" (see last row of Table VI) is rather uncertain because—due to lack of further data—it has been assumed to be the same as the value for PH(3B), rounded to 1 significant figure (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, it is more likely to be overestimated than underestimated.

4.2. Results of the Environmental Assessment of the Large-Scale Production of Bio-Based Polymers

This section 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.

As Table VII shows the energy savings potential in 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. The potential GHG emission reductions by 2010 due to bio-based polymers range from 1.8 to 3.5 million t CO₂ eq depending on the extent to which P&Ms are implemented. By 2020, 3.0 to 8.5 million t CO₂ eq could be saved. These appear to be quite substantial savings which will be discussed and put into perspective in Section 5.

Table VII further shows that the additional land requirements by 2010 due to bio-based polymers ranges between 63 and 125 thousand hectares depending on the extent to which P&Ms are implemented. By 2020, additional land

Table VII. Summary of savings resulting from large-scale production of bio-based polymers in Europe compared with petrochemical polymers 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	500/1000 ¹ ECCP, 2001
2010	500	1,000	1,000	
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	2.0/4.0 ¹ ECCP, 2001
2010	1.8	3.5	3.5	
2020	3.0	6.0	8.5	
Specific energy savings, GJ/(ha ^a a)				
2002	296	296	296	
2010	400	400	400	
2020	389	389	122	
Specific GHG em. red., t CO ₂ eq/(ha ^a a)				
2002	17.2	17.2	17.2	
2010	28.0	28.0	28.0	
2020	26.7	26.7	8.7	

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

requirements have increased by up to 225 million hectares in the scenarios "WITHOUT P&Ms" and "WITH P&Ms," while they are very substantially higher in the "HIGH GROWTH" scenario (975 million hectares). This is due to the product category "Other bio-based polyesters, PURs and PAs" which has been assumed to emerge only in the HIGH GROWTH scenario and for which the land use in hectares per tonne of polymer is estimated to be four to six times larger than for PLA and starch polymers (see Table VI).

5. DISCUSSION

As discussed in Section 4 the potential energy savings by 2010 due to bio-based polymers range from 25 to 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 2000³¹ these savings are equivalent to (Table VIII):

- 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).

³¹Energy consumption by the EU chemical industry in primary energy terms (including feedstocks) amounted to 5600 PJ in 2000.³¹

Table VIII. Emission projections for petrochemical polymers and of bio-based polymers in perspective.

		2000	2002	2010	2020
Petrochemical 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%
Compensatory 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%

¹Calculated with a weighted overall value of 88 GJ/t polymer. ²EU chemical industry energy use including feedstocks: 5600 PJ in 2000 (IEA, 2003). ³EU total energy use (all countries, entire economy): 61400 PJ in 2000 (IEA, 2003). ⁴Calculated with a weighted overall value of 5 t CO₂/t polymer. ⁵EU chemical industry emissions: 175 Mt CO₂ in 1998 (CEFIC, 2001); scaled to figure for 2000 of 177 Mt. ⁶EU total emissions (all countries, entire economy): 4165 Mt CO₂ in 2000. ⁷100% = Full compensation (reduction due to bio-based polymers equal to increase due to petrochemical polymers).

The potential GHG emission reductions by 2010 due to bio-based polymers range between 1.8 and 3.5 million t CO₂ eq/t depending on the extent to which P&Ms are implemented and by 2020, 3.0 to 8.5 million t CO₂ eq/t could be saved. Relative to the total CO₂ emissions from the EU chemical industry in 2000^j 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).

To summarize, the savings of non-renewable energy and GHG emissions amount to a maximum of 2–5% in 2020. It must be emphasized that the relatively low contributions have their reason in the comparatively low production volumes of bio-based polymers until 2020. Today 66 grams of bio-based polymers are produced per

^jCO₂ emissions from the EU chemical industry amounted to 175 Mt CO₂ in 1998;¹² Scaling with CEFIC index CO₂ emissions 2000 versus 1998, one obtains 177 Mt.¹³ This figure includes only CO₂ emissions from energy use, i.e., from the production of process heat, steam and electricity; CO₂ emissions from non-energy use are excluded.

capita in Europe and the per-capita values by 2020 range between 2.3 kg/(cap*a) in the scenario "WITHOUT P&M" and 7.9 kg/(cap*a) in the "HIGH GROWTH" scenario which remains far below the current production and use of petrochemical polymers (approx. 120 kg/(cap*a) in 2000). However, the production of petrochemical polymers is still rapidly growing. As shown in Table VIII 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). The cradle-to-grave CO₂ 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.^k This is 15 to more than 40 times more than the emissions saved by bio-based polymers in the three scenarios WITHOUT

^kIn line with the calculations in this paper for bio-based polymers the cradle-to-grave CO₂ emissions reported in Table VIII for petrochemical polymers do not account for possible credits related to energy recovery.

P&M, WITH P&M and HIGH GROWTH.¹ This shows that the lower specific environmental impact of bio-based polymers will not be able to compensate for the additional environmental impacts caused by the expected high growth of petrochemical plastics.

When explaining the input data used (Tables V and VI) it was pointed out that a few simplifying assumptions are made which could result in overestimation of the energy and CO₂ savings. This potential overestimation is not of concern in view of the relatively low contribution of bio-based polymers to emission reduction at the EU level and the greater increase in absolute terms of emissions due to petrochemical polymers in line with their continued growth. In other words, lower values for the input data would not change the overall picture of this analysis.

The additional land use in thousands of hectares per annum (see Table VII) can be put into perspective by comparing it with total land use in EU15 for various purposes. Table IX shows the additional land use as a proportion of the total land use in EU15 for wheat (2002),²⁵ cereals (1997), set-aside land (1997) and industrial crops (1997) Ref. [24].^m 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.ⁿ 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.

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.^o If the assumption is made that agricultural land will be utilised that would otherwise

¹See the last row of Table VIII; the reciprocal of this number gives the factor by which the emission increases due to petrochemical polymers exceed the emission reductions due to bio-based polymers.

^mAssume 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.

ⁿThis proportion is probably already significantly lower in 2003 terms since according to the European Commission's Directorate General for Environment and Climate (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.³⁶

^oEmployment in the chemical industry is expected to be comparable to petrochemical polymers, therefore resulting in no net additional employment.

Table IX. 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).

be set aside or used in a less productive manner, then the production of bio-based polymers can be expected to lead to increased employment in cultivation and harvesting of starch and sugar crops. However, we estimate the additional employment in the agricultural sector to reach only up to 500 full-time equivalents (FTEs) by 2010 and by 2020 the expected additional employment amounts to less than 1000 FTEs in the scenario "WITH P&Ms" and around 4000 FTEs in the scenario "HIGH GROWTH." 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 discussed in Section 3. Employment effects are hence found 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 a value of 0.08 percent is reached.

6. CONCLUSIONS

Summarising the potential environmental and socio-economic effects it may be concluded that while the environmental effects of bio-based polymers in *specific* terms (i.e., per tonne polymer) are high, effects in absolute terms relative to those of total industry or society are low in the short to medium term. 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 by 2020, the production of petrochemical polymers is likely to be 20 to 40 times larger than that of bio-based polymers. This also explains why bio-based polymers will not be able to compensate for the additional environmental impacts caused by the expected high growth of petrochemical plastics until 2020.

Nevertheless bio-based polymers represent a worthwhile strategy for gradually reducing the environmental burden by replacing fossil with bio-based resources and at the same time reducing the oil-dependence of the chemical sector, hedging the related economic risks and reducing the sector's GHG emissions. The development and production of bio-based polymers represent first steps towards a sustainable polymer sector.

While the bio-based polymer sector is developing very dynamically, it is a consequence of the low starting level that it takes more time until meaningful substitution levels are observed, which are then also accompanied by sizable benefits. In order to realize more substantial changes than outlined in this paper, a longer time period is required.

This may also require a technology boost from Industrial Biotechnology (referred to in Europe as White Biotechnology; see Ref. [10]) and innovative thermochemical processes using biomass as a feedstock. These bio-based production processes represent alternatives not only to conventional oil-based processes but also to chemicals derived from coal. All these options are in competition with each other⁴⁴ and the economic boundary conditions and the policies and measures set at the national and international level will strongly influence the role of each.

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