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Applications of life cycle assessment to NatureWorks™ polylactide (PLA) production

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Abstract

NatureWorks™ polylactide (PLA)[1] is a versatile polymer produced by Cargill Dow LLC. Cargill Dow is building a global platform of sustainable polymers and chemicals entirely made from renewable resources. Cargill Dow's business philosophy is explained including the role of life cycle assessment (LCA), a tool used for measuring environmental sustainability and identifying environmental performance-improvement objectives. The paper gives an overview of applications of LCA to PLA production and provides insight into how they are utilized. The first application reviews the contributions to the gross fossil energy requirement for PLA (54 MJ/kg). In the second one PLA is compared with petrochemical-based polymers using fossil energy use, global warming and water use as the three impact indicators. The last application gives more details about the potential reductions in energy use and greenhouse gasses. Cargill Dow's 5–8 year objective is to decrease the fossil energy use from 54 MJ/kg PLA down to about 7 MJ/kg PLA. The objective for greenhouse gasses is a reduction from +1.8 down to −1.7 kg CO_2 equivalents/kg PLA.

Keywords: Cargill Dow; Sustainability; Life cycle assessment (LCA); Eco-profile; NatureWorks; Polylactide (PLA); Polylactic acid

1. Introduction

In 1988 a project to develop polylactide (PLA) was launched by Cargill Inc. The project goal was to establish new product and value opportunities for starch processed by the company. Dr. Pat Gruber, now vice president and chief technology officer for Cargill Dow, was the initiator and project champion. Along with a small group of scientists, Dr. Gruber developed key processes for conversion of lactic acid into lactide, and processes and technologies for purification and polymerization/devolatilization of lactide. In 1994 the company built a 5000 metric tons per year PLA facility in Savage, Minnesota to prove and further develop lactic acid to PLA technology on a semi-works scale and to catalyze the development of a commercial market for PLA. In early 1995 Cargill realized it needed a partner with a strong presence in the polymer market. Cargill assembled a list of partner attributes and Dow emerged as the best candidate. In November 1997 Cargill Dow LLC was founded as a 50/50 joint venture between Cargill Inc and The Dow Chemical Company to pursue the commercialization of PLA polymers under the trade name NatureWorks™.

A stand-alone company today, Cargill Dow is building a global platform of sustainable and versatile polymers and chemicals entirely made from renewable resources. To achieve its objectives, Cargill Dow is using and further refining an optimal combination of agricultural processes and biological and chemical technologies. Cargill Dow's philosophy is that its business system should be sustainable from an economic, environmental and social perspective, the so called "triple bottom line" of sustainability [1]. Cargill Dow uses life cycle assessment (LCA) as a tool for measuring environmental sustainability and identifying environmental performance improvement objectives.

As of January 2002, Cargill Dow employed more than 250 people worldwide. Cargill Dow has its headquarters in Minnetonka, Minnesota, USA with additional offices in Naarden, The Netherlands and Tokyo, Japan. Cargill Dow has now expanded its capacity by building the world's only commercial production facility for PLA in

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Nomenclature

B/WP	Biomass/wind power
CWM	Corn wet mill
GER	Gross energy requirement
GFEU	Gross fossil energy use
LA	Lactic acid
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Mega joules
PFD	Process flow diagram
PLA	Polylactide
WWT	Waste water treatment

Blair, Nebraska, USA. At full production, the Blair facility, which began operations in late 2001, can produce 140,000 metric tons of PLA per year [2].

2. PLA production technology

Cargill Dow's polylactide (PLA) is a versatile new compostable polymer that is made from 100% renewable resources like corn, sugar beets or rice. Fig. 1 illustrates the various steps involved in the production of PLA starting with corn growing and ending with the production of PLA granules.

Today, the PLA life cycle starts with corn. All free energy consumed by biological systems arises from solar energy that is trapped by the process of photosynthesis. The basic equation of photosynthesis is:

$$H_2O + CO_2 \xrightarrow{\text{light}} (CH_2O) + O_2$$

In this equation, (CH_2O) represents carbohydrate, primarily sucrose and starch. So, all the carbon, hydrogen and oxygen in the starch molecule as well as in the final polylactide molecule have their origin in water and carbon dioxide. After harvesting, the corn is transported to a corn wet mill where the starch is separated from the other components of the corn kernel (proteins, fats, fibers, ash and water) and converted via enzymatic hydrolysis into dextrose. Cargill Dow ferments dextrose into lactic acid at near neutral pH. Via acidulation and a series of purification steps the lactate salt fermentation broth is then purified to yield lactic acid.

The first generation of PLA will be produced from the annually renewable resource corn, the cheapest, starch-rich and most widely available raw material in the USA. In other parts of the world, locally available crops such as rice, sugar beets, sugarcane, wheat and sweet potatoes can be used as a starch/sugar feedstock. Cargill Dow is also working to develop new conversion technologies to facilitate the use of lignocellulosic biomass feedstocks, such as corn stover (the residue left in the field), grasses, wheat and rice straws, and bagasse (the residue of sugarcase production).

There are two major routes to produce polylactic acid from the lactic acid monomer: direct condensation polymerization of lactic acid and ring-opening polymerization through the lactide intermediate. The first route involves the removal of water by condensation and the use of solvent under high vacuum and temperature. With this route only low- to intermediate-molecular-weight polymers can be produced, mainly because of the presence of water and impurities. Other disadvantages of this route are the relatively large reactor required, and the need for evaporation, recovery of the solvent and increased color and racemization. Mitsui Chemicals developed a new process based on direct polycondensation of L-lactic acid to enable the production of high molecular weight PLA without the use of an organic solvent [3].

Cargill Dow uses the second route: ring-opening polymerization through the lactide intermediate [4]. In the first step of the process water is removed under mild conditions (and without the use of a solvent) to produce a low moleculer weight prepolymer. This prepolymer is then catalytically depolymerised to form a cyclic intermediate dimer, referred to as lactide which is then purified to polymer grade using distillation [5]. The purified lactide is polymerized in a solvent free ring-opening polymerization and processed into polylactide pellets [6]. By controlling the purity of the lactide it is possible to produce a wide range of molecular weights.

Because there are four unique groups attached to the central carbon atom, lactic acid is a chiral molecule. Chiral molecules exists as 'mirror images' or stereoisomers. The optically active lactic acid has an "L" and "D" stereoisomer. "L" and "D" are also referred to as *R* and *S*. D = *R* = right handed and L = *S* = left handed. Chemically synthesized lactic acid gives the racemic mixture (50% D and 50% L). Fermentation-derived lactic acid typically consists of 99.5% of the L-isomer and 0.5% of the D-isomer. Production of the cyclic lactide dimer results in three potential forms: the D,D-lactide (called D-lactide), L,L-lactide (called L-Lactide) and L,D or D,L lactide called meso lactide. Meso lactide has different properties from D and L lactide. The D and L lactide are optically active, but the meso is not. Before polymerization the lactide stream is split into a low D lactide stream and a high D/meso lactide stream. Ring-opening polymerization of the optically active types of lactide can yield a 'family' of polymers characterized by the molecular weight distribution and by the amount and the sequence of D-lactide in the polymer backbone. Polymers with high L-lactide levels can be used to produce

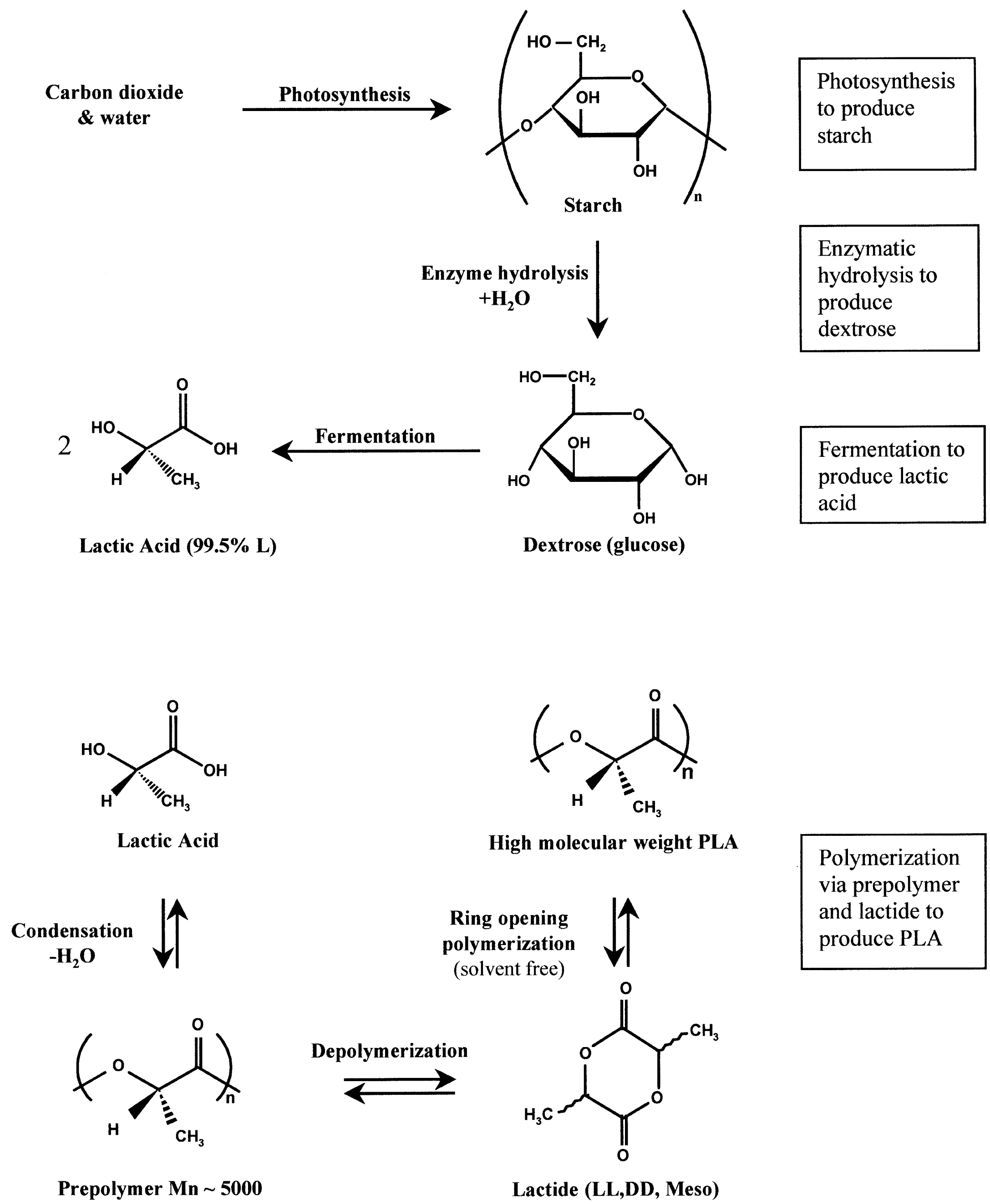


Fig. 1. PLA manufacturing overview.

crystalline polymers while the higher-D-lactide materials are more amorphous.

3. NatureWorks^{TM} PLA applications

Cargill Dow's NatureWorks^{TM} branded PLA is a compostable polymer used in a wide range of packaging (primarily for food), film and fiber applications. Table 1 provides an overview of Cargill Dow's current business segments with examples of commercially available applications [7,8].

4. Cargill Dow's business philosophy and definition of sustainability

In recognition of the opportunity and need for sustainable, renewably-sourced plastics, Cargill Dow has adopted an ambitious statement of business philosophy:

"*Cargill Dow is the leader in producing plastics from renewable resources, and is dedicated to meeting the world's needs today without compromising the earth's ability to meet the needs of tomorrow.*"

Table 1
Cargill Dow business segments

	Business segment	Commercially available applications
1	Rigid thermoforms	— Clear, short shelf life trays & lids — Opaque dairy containers — Consumer displays & electronics packaging — Disposable articles — Cold drink cups
2	Biaxially-oriented films	— Shrink wrap for consumer goods packaging — Twist wrap candy and flower wrap — Windows for envelopes, bags and cartons
3	Bottles	— Short shelf-life milk and oil packaging
4	Apparel	— Sport, active and underwear — Fashion
5	Non-wovens	— Agricultural and geo textiles — Hygiene products (diapers and feminine hygiene) — Wipes — Shoe liners — Blends with natural fibers–hemp, sisal and flax
6	Household, industrial and institutional fabrics	— Bedding, drapery, table cloths, curtains, mattress ticking — Wall and cubicle fabrics, upholstery
7	Carpet	— Surfase yarns & fibers
8	Fiberfill	— Pillows — Comforters — Mattresses — Duvets
9	Foams	— Structural protective foams
10	Lactide	— Raw material for ethyl lactate production, a high purity solvent

Stated another way, Cargill Dow seeks to be sustainable in its processes and activities, and to sell a product that contributes to sustainability wherever it is used. The concepts of sustainability and sustainable development have become increasingly important in a world where many fear vital natural resources and ecosystem services are threatened or in decline. According to the Living Planet Report 2002 of the World Wide Fund current trends are moving humanity away from achieving the minimum requirements for sustainability, not towards it [9]. According to the 2002 OECD report 'Working Together Towards Sustainable Development' there are still many pressing challenges and strengthened action to address them are needed now. These challenges include the establishing of appropriate policies to combat the threat of climate change, to better manage fisheries and water resources, and to provide greater protection of ecosystems and biodiversity. These policies would result in a more marked decoupling of environmental pressures from economic growth by changing unsustainable consumption and production practices. A better integration of the social, economic and environmental dimensions of sustainable development are needed [23]. The notion behind sustainability is that with careful thought and innovative practice, economies and societies can improve without degradation to natural environments. Ideally, sustainable development means that activities that improve economic and social welfare simultaneously improve environmental conditions as well.

Cargill Dow defines sustainability based on a triple bottom line approach in which economic sustainability, environmental sustainability and social responsibility are pursued and maximized simultaneously [10]. Although implementation of this concept is challenging in practice, explaining it is relatively simple. Economic sustainability is about building and growing a viable business that provides markets for agricultural products, new career opportunities for researchers and staff, and other economic benefits to investors and society. For a "start-up" company like Cargill Dow, economic sustainability is measured against fairly traditional financial and operations targets, including return on investment and operating revenues netted against expenses. From a societal perspective, economic sustainability also involves the development of robust and enduring markets for sustainable goods and services.

Social sustainability is reflected in social responsibility, and involves concepts of equitable opportunity for all participants in the value chain as well as strong bias against business and operational practices that take unfair advantage of particular segments of society. From Cargill Dow's perspective, social sustainability implies that business success must not disadvantage, for example, feedstock suppliers (farmers). More broadly, the environmentally friendly production processes and compostability and recyclability of PLA products helps to ensure that production, use and ultimate disposal of products do not impose disproportionate burdens on any particular segment of society. For example, Cargill Dow has eschewed the use of potential endocrine disrupters in its products and refuses to allow PLA use in tobacco products and packaging.

Environmental sustainability is about making products that serve useful market and societal functions with less environmental impact than currently available alternatives. Moreover, environmental sustainability necessarily implies a commitment to continuous improvement in environmental performance. The key measurement tool for environmental sustainability is life cycle assessment.

The ideal environmentally sustainable product provides equivalent function as products it replaces and is available at competitive costs. It is made from renewable resources, can itself be constantly renewed without degradation in quality or performance, and has a minimum environmental impact. Such a product is made using only substances known to be safe for both humans and the environment. Ideally the life cycle of the sustainable product is in balance with the surrounding ecosystem. These attributes describe Cargill Dow's environmental goal for PLA.

Although LCA is an extremely valuable part of the company's strategy, Cargill Dow's full range of environmental sustainability efforts extends beyond its commitment to using LCA. The company has adopted product development and design rules that seek to ensure that the natural resource-base values of its products are not compromised. The company works with fabricators and processors to ensure that additives, blends, treatments and other compounds do not create a substantial risk to human health or the environment, either in application, use or disposal. Cargill Dow has adopted and employs contractual provisions strengthening both up- and downstream influence and control of supply chain activities. Other business practice activities include sustainability reviews of business rules and the development of an internal employee training program on sustainability. And several key employees have explicit responsibility to support the company's mission of improving and integrating every component of the triple bottom line of environmental, economic and social sustainability.

Plastics and polymers have become an essential element of modern life and can play a key role in global progress toward sustainability. It is estimated that 150 million tons of polymers are produced from fossil fuels today, and that production is increasing at a rate of approximately 4–5% per year. This growth is fueled by the many inherent advantages of plastics, including low weight, high strength, wide application range, and maturity of the underlying manufacturing technologies. Plastics extend storage life of perishables such as food or medicine, and reduce environmental impacts associated with transportation by reducing package or vehicle weight. Polymer-based fibers will play an increasingly important role in providing clothing for the world's rapidly growing population.

The advantages of plastics and their use also lead to some of the greatest concerns about fossil fuel-based materials. Use of fossil fuels for polymers will increasingly compete with use of fossil fuels for transportation and industrial purposes, especially as exploration and production costs of fossil fuels rise due to the finite nature of the underlying resource. The durability of many plastics, under both aerobic and anaerobic conditions, contributes to growing waste and waste disposal problems. Even improving recycling rates for many types of plastics have not kept up with increases in overall plastics consumption. And in some cases recycling yields new problems associated with concentration of contaminants through the recycling process.

In all, and over the long run, Cargill Dow's development of PLA is based on finding a solution that both provides society with the benefits of plastics and polymers, and at the same time eliminates adverse environmental impacts and supports sustainable development. As polymers are increasingly derived from agricultural feedstocks, Cargill Dow is working toward a future in which the agricultural processes for producing feedstocks becomes increasingly restorative—to agricultural ecosystems, agricultural communities, and agricultural economies—as well.

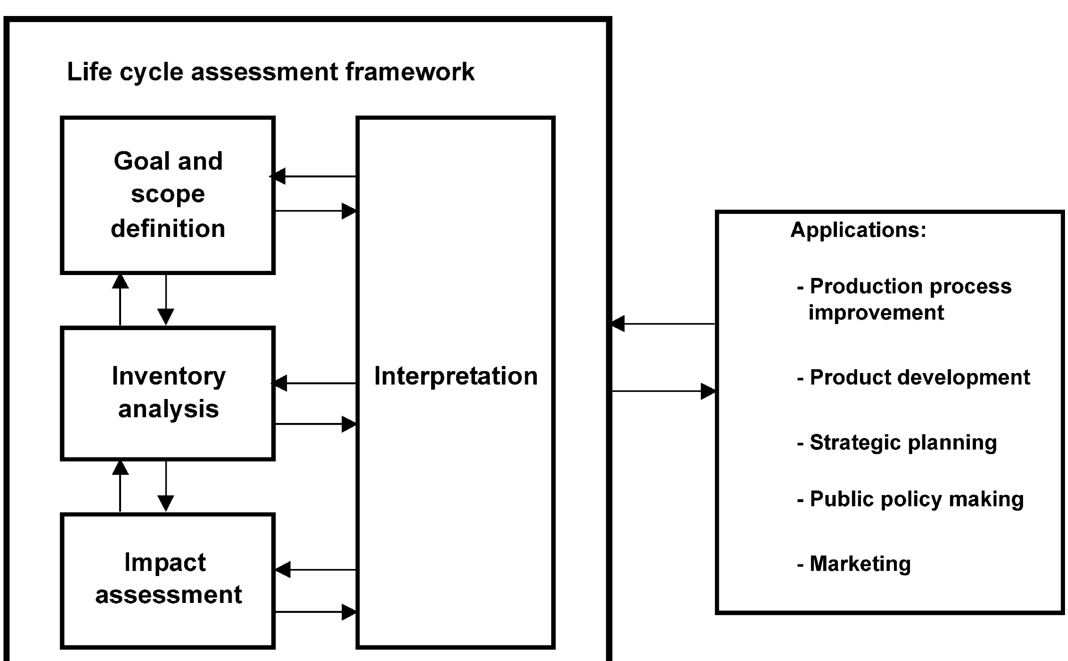
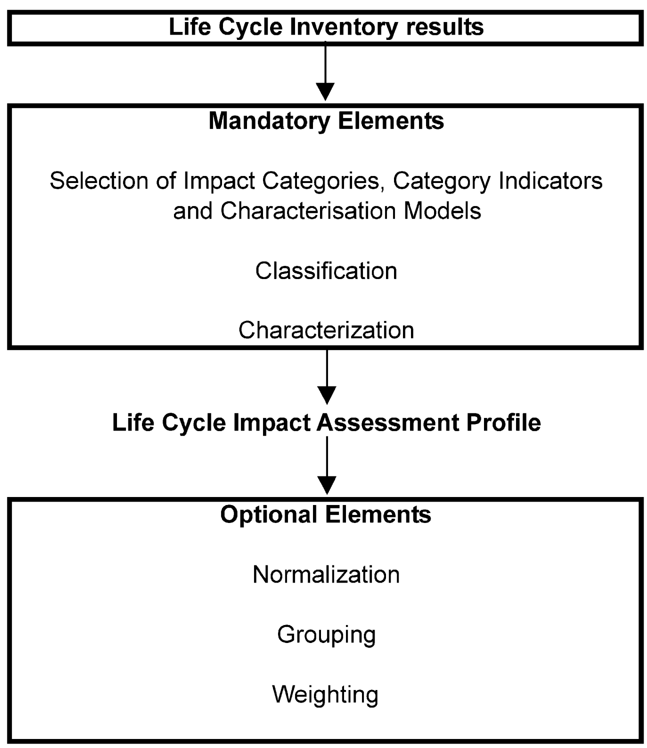


Fig. 2. Phases of a life cycle assessment.

5. LCA, a tool for measuring environmental sustainability

Life cycle assessment (LCA) is a method to account for the environmental impacts associated with a product or service. The term 'life cycle' indicates that all stages in a product's life, from resource extraction to ultimate disposal, are taken into account.

The four phases of LCA [11] are displayed in Fig. 2. Goal and scope definition serves to define the purpose and extent of the study, and it contains a description of the system studied. An important issue is the basis for comparison of different systems- the functional unit of a product or service delivered. The second phase, inventory analysis, consists of data collection and analysis [12]. Data on the environmental interventions (emissions, land use, resource use, noise etc.) connected to each process in the life cycle is collected, often guided by a process flow diagram. This data processing is not always straightforward. For processes that produce more than one output, e.g. a corn wet mill, decisions are required about how to allocate the environmental burdens to each output. The third phase, impact assessment, serves to evaluate the significance of the environmental interventions contained in a life cycle inventory. In practice, an inventory will contain a long list of emissions and resource uses. The purpose is to determine the relative importance of each of these inventory items and to aggregate interventions to a small set of indicators, or even to a single indicator. This is done in order to identify those processes which contribute most to the overall



Classification: Assignment of inventory data to different impact categories, such as global warming and acidification.

Characterisation: Calculation of category indicator results for each impact category using characterisation factors.

Normalisation: Impact/damage categories have different units. Normalisation is used to make these categories dimensionless.
Normalised results show the contributions relative to the contributions of these categories in a reference area over a certain period: Europe or the World.

Grouping: Assigning of impact categories to groups of similar impacts or ranking categories in a given hierarchy (low, medium and high priority).

Weighting: Converting indicator results of different impact categories to a common scale, based on value choices. This can finally include aggregation to a single indicator.

Fig. 3. The sequence of elements in life cycle impact assessment according to ISO 14042.

impact, or to compare products. As Fig. 2 indicates LCA can be seen as an iterative process where interpretations may lead to an adjustment of the goal and scope or further investigations of the inventory and associated impacts.

According to standard 14042 of the International Standard Organisation (ISO), life cycle impact assessment (LCIA) consists of two mandatory elements, classification and characterisation, and a series of optional elements, normalisation, grouping, and weighting [13]. These elements and the sequence of events are described in Fig. 3. A fourth phase, interpretation, is to evaluate the study in order to derive recommendations and conclusions [14].

Although the science of life cycle assessment has increased in sophistication in recent years, the process can only account for the impact categories actually inventoried. It is probably impossible to inventory all impacts. The combination of impact categories requires weighting; weighting of categories requires value judgements; and therefore weighting is the most critical and controversial step in LCIA. Nevertheless, in a world where every human activity has environmental impacts, it is important to strive for the best informed conclusions possible.

Cargill Dow uses LCA and compiles Life Cycle Inventories (LCI) for a variety of applications:

1. LCA/LCI improves insight about the PLA production chain, highlighting areas in which PLA does well, areas of potential concern, and areas where more data is required. As a result, careful LCA can help prioritize efforts to improve environmental performance.
2. LCA/LCI information is used to make further environmental/economic improvements in the PLA production chain, such as process improvements and the selection of raw materials, energy sources, production locations and waste management routes.
3. Information collected through an LCI/LCA process provides insight into how to position PLA products in the marketplace.
4. The results of LCA are useful to Cargill Dow in achieving transparency and in responding to requests for information.
5. LCI data can be used to calculate contributions to particular impact categories. This information is used to benchmark environmental performance against the petrochemical polymers and other incumbent competitor products.
6. Published LCI/LCA data for PLA can be used by external LCA practitioners (governmental agencies, academics, non-governmental organizations, customers and consumers) in performing and improving their own studies.

The following section will provide insight into how Cargill Dow utilizes LCA.

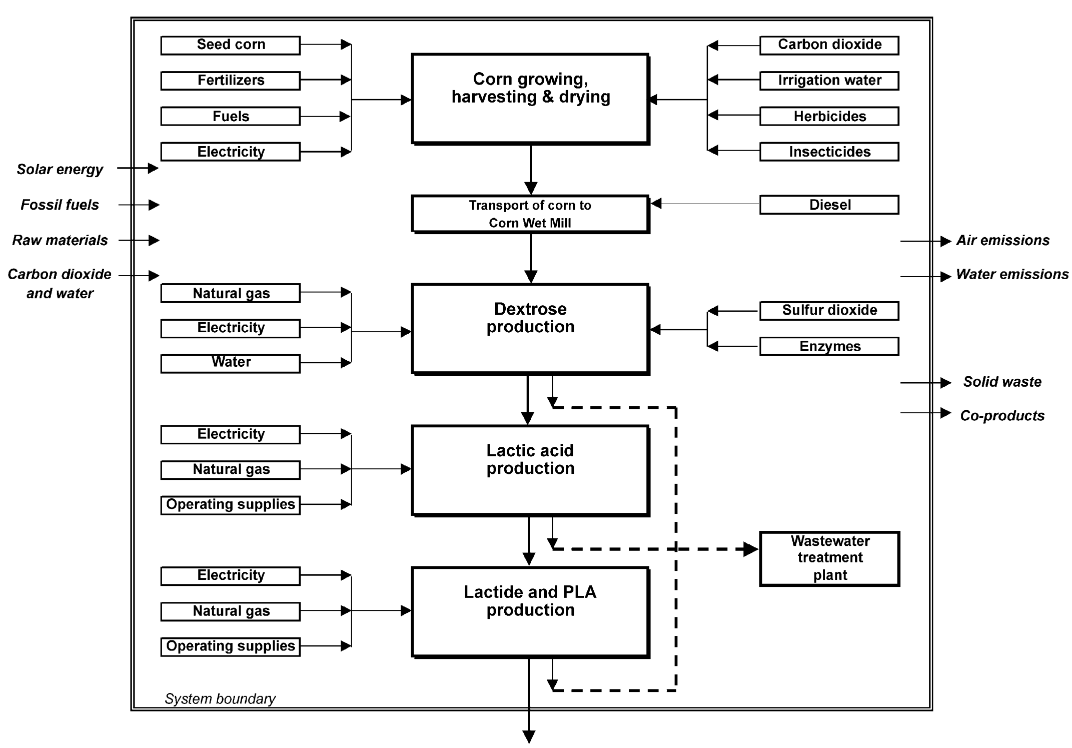


Fig. 4. Simplified flow diagram and system boundary of PLA production system.

6. Ecoprofiles for PLA

6.1. Description of the PLA1 production system

Cargill Dow's efforts at developing a comprehensive life cycle inventory for PLA pellet production span several years. Fig. 4 is a simplified flow and system boundary diagram for PLA as produced by Cargill Dow at the Blair, Nebraska facility. This PLA production system is indicated with "PLA1". The analysis depicted includes impacts associated with:

- corn growing,
- transport of corn to the corn wet mill,
- processing of corn into dextrose,
- conversion of dextrose into lactic acid,
- conversion of lactic acid into lactide, and
- polymerization of lactide into polylactide.

Corn growing includes inputs such as corn seed, fertilizers, electricity and fuel (natural gas, diesel, propane and gasoline) used by the farmer, atmospheric carbon dioxide take up through the photosynthesis process, irrigation water and pesticides. On the output side, emissions such as dinitrogenoxide, nitrates and phosphates were taken into account. Also the production of the tractors and combine harvesters used was investigated with the outcome that those contributions were negligible. The corn wet mill converts the starch in the corn grain into dextrose syrup, corn gluten feed, corn gluten meal and corn germ. Inputs include energy, water, sulfur dioxide and enzymes. Dextrose is converted to lactic acid utilizing fermentation and a series of purification steps. Lactic acid is converted to its cyclic dimer, lactide, which is purified using distillation. The lactide is polymerized in a solvent-free ring opening polymerization and processed into pellets. These pellets are the final stage of the PLA ecoprofile. Energy and operating supplies (such as process water, cooling water, nitrogen, compressed air, catalysts, stabilizers and chemicals) are all accounted for in the ecoprofile, as is wastewater treatment. The energy as well as operating supplies consumption by the wastewater treatment plant are also included. Proprietary concerns prohibit providing details on all specific inputs. The corn wet mill, as well as the lactic acid and PLA plant, are located on the same site, so no significant additional transport is required between those operations.

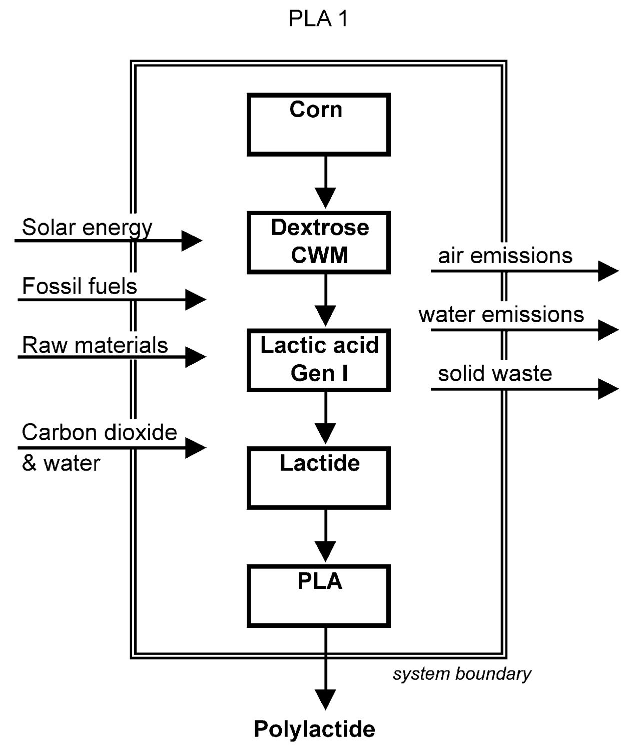


Fig. 5. System boundary for PLA production.

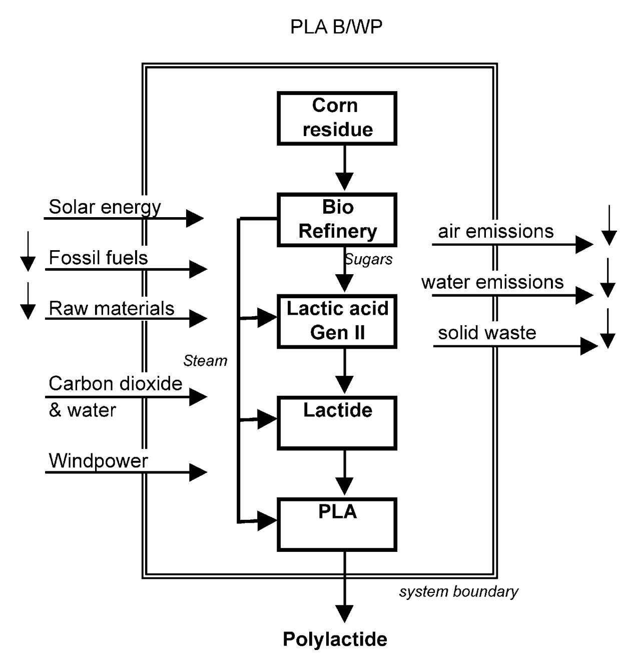


Fig. 6. System boundary for PLA production with biomass feedstock and wind energy input.

6.2. PLA1 and PLA B/WP

The process flow diagram in Fig. 4 is further simplified in Fig. 5, which provides a system boundary for the production process at the PLA facility in Blair, Nebraska. To distinguish it from future, biomass-based processes, it is hereinafter referred to as "PLA1."

Fig. 6 represents the next-generation PLA facility (5–8 years) objective for Cargill Dow, hereinafter referred to as "PLA B/WP". The 'B' stands for Biomass and the 'WP' for Wind power. The facility and process will differ from PLA1 in five key ways:

1. Instead of corn-derived dextrose, the primary feedstock is crop residue (stems, straw, husks, and leaves) from corn or other crops;
2. The cellulose and hemicellulose will be converted into fermentation sugars in a so-called bio-refinery. The remaining lignin-rich fraction will be combusted or gasified to produce steam which will in turn provide thermal energy for the various conversion processes;
3. The lactic acid production process will be further optimized to increase yield and reduce raw material use among other improvements;
4. Instead of electricity from the Nebraska grid, the additional required electricity inputs will be derived from wind power; and
5. Further optimization of the energy efficiency of the lactide and polymer facilities.

All these improvements and changes will lead to lower fossil fuel and raw material use as well as lower air emissions, water emissions and solid waste production.

6.3. Methodology, software and data used

As a renewably-derived source of plastics, PLA competes most directly in the marketplace with traditional plastics, most of which are derived from petroleum. In Europe, where LCA/LCI studies are more commonly used and better developed, the Association of Plastics Manufacturers of Europe (APME) has over the last 10 years published a series of ecoprofiles for traditional petrochemical based polymers [15]. In order to allow for the most meaningful comparisons, Cargill Dow undertook the development of ecoprofiles for PLA using the same methodology [16], software, and core databases as used in the APME analyses [17]. In addition, the results are presented in the same format, that used by Boustead Consulting, the organisation that calculated these ecoprofiles for the European industry.

Cargill Dow's development of PLA ecoprofiles, as well as the harmonization of these ecoprofiles with the APME methodology, has required new data and analysis, as well as engineering estimates. Public average corn growing data from Nebraska and Iowa, the most likely sources of corn for the Cargill wet mill, was used for the corn production. Data representative for the Cargill corn wet mill that will supply Cargill Dow was used for the dextrose production step. At the time of writing of this article, the Cargill Dow lactic acid plant in Blair, Nebraska has not yet been commissioned for commercial operation. As a result, data for lactic acid production and purification is based on detailed design plans and engineering estimates. Also the data for lactide production and PLA polymerization come from the detailed design plans for the Lactide/PLA plant that was started up in Blair in November 2001, and will be supplemented over time based on actual operating experience, subject to confidentiality concerns associated with Cargill Dow's one-of-a-kind facilities and operations. Data for the conversion of (ligno)cellulose into sugars in a biorefinery was based on a study performed by NREL for Cargill Dow [18]. Data for producing and delivering natural gas and most of the operating supplies was taken from the Boustead Core databases and is subject to the limitations inherent in that source, including estimation, variability, and aggregation or averaging to protect confidentiality. For other important inputs, such as electricity, recent data was collected from the regional suppliers.

6.4. Cargill Dow's publication plan and limitations

Recognizing that increased transparency is inherent in progress toward sustainability, Cargill Dow plans a series of LCA/LCI-related publications in peer reviewed journals over the next two years. These articles will report detailed representative corn production data, corn wet milling process data, lactic acid and polylactide production process data, and disposal or recycling data. In striving for this increased openness, the challenge facing Cargill Dow is that as the sole commercial producer of PLA, publication of too much specific data threatens to reveal trade secrets and confidential commercial information. Incumbent competitors in a mature market space enjoy the opportunity to use industry averages to obscure individual facility performance or process attributes; Cargill Dow's data is the industry average data for PLA. Proprietary concerns will likely continue to prohibit exact disclosure of Cargill Dow's processes, though much information can be shared under appropriate confidentiality agreements.

7. Applications of life cycle assessment to PLA production

Optimally, LCA is performed on a cradle-to-grave basis. That is, the assessment includes all inputs and outputs, aggregated in a series of impact categories, extending from the production of raw materials (the "cradle") to the final disposal of all possible consumer products (the "grave"). As described above in Table 1, PLA is a versatile polymer with many applications, and a wide-ranging potential life cycle. Much of Cargill Dow's detailed LCA studies have been in regard to specific product applications. Due to the sensitive nature of Cargill Dow's and customers' LCI data these studies have not been published. The best source for data underlying the values presented in this section is the SRI study on the life cycle for polylactide [19]. This SRI study utilizes a variety of data available in the public domain to support a fossil energy and greenhouse gas emissions life cycle inventory for PLA.

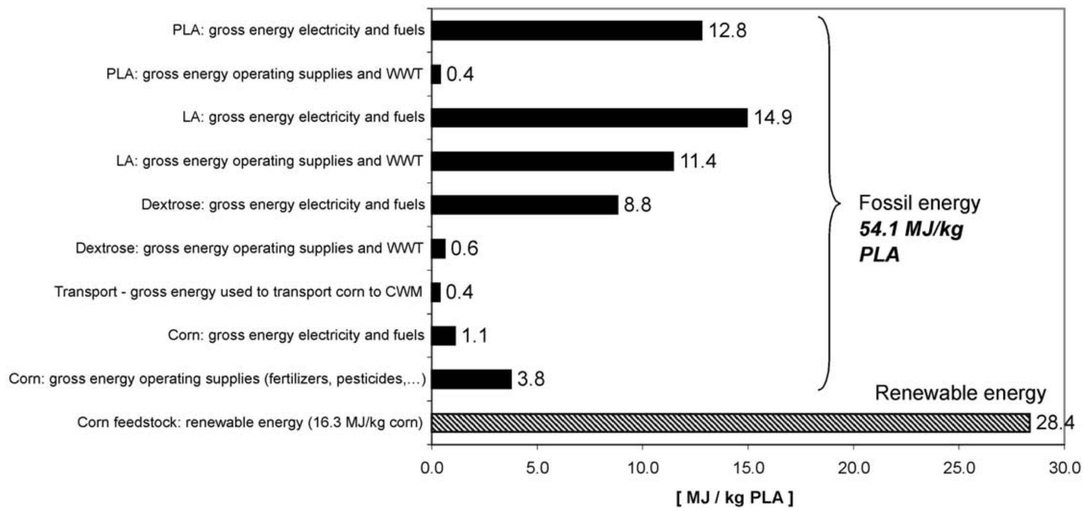


Fig. 7. Contributions to the gross energy requirement for PLA1.

The focus of this section is on the environmental performance of PLA as measured by three life cycle impact categories: fossil energy requirement, greenhouse gasses and water use. Section 7.1 gives more details about the contributions to the gross energy requirement for PLA1. In Sections 7.2–7.5, PLA1 and PLA B/WP are compared with the traditional polymers using fossil energy use, greenhouse gasses and gross water use. Finally, sections 7.6 and 7.7 provide more insight about the potential reductions that can be achieved by using the PLA B/WP scenario.

7.1. Contributions to the Gross Energy Requirement for PLA1

Fig. 7 gives the contributions to the Gross Energy Requirement (GER) for PLA1. The GER for PLA1 is 82.5 MJ/kg accumulated for the life cycle from corn growing through the production of ready-to-ship pellets. The production system for PLA1 is set forth in Fig. 4.

- The 28.4 MJ represents the corn feedstock (15.5% moisture) used to produce 1 kg PLA. This is the *renewable* energy part and defined using the heat of combustion of corn (16.3 MJ/kg corn). This part is fixed and can only be decreased by using less corn.
- The gross *fossil* energy use (GFEU) is 54.1 MJ/kg of PLA, equivalent to the gross energy requirement (GER) less the energy embodied in the corn feedstock (calculated as 82.5–28.4 = 54.1 MJ/kg). The most important contributors to GFEU are: coal, oil, gas and nuclear. The GFEU should be considered as the most relevant data point, because it is an indicator for the use of fossil energy as well as for the translocation of carbon from the earth into the atmosphere together with the linked emissions such as sulfur oxides, hydrocarbons and heavy metals. A primary environmental sustainability objective of Cargill Dow is to reduce the use of fossil energy in the PLA production system by shifting from fossil resources to renewable resources (see also Section 7.2). A secondary objective is also to reduce the absolute production energy used in the several processes.
- The GFEU to grow corn and ship it to the corn wet mill (CWM) is the sum of gross energy inputs relating to operating supplies at the farm (3.8 MJ/kg), electricity and fuels used at the farm (1.1 MJ/kg), and energy for transportation of corn to the corn wet mill (0.4 MJ/kg). These inputs represent 9.8% of the GFEU for PLA, and due to the maturity of the corn agribusiness sector, are not expected to change significantly in the foreseeable future. Even when/if plant science makes significant improvements here, they will have a small effect overall.
- The GFEU to convert the corn starch into dextrose is 9.4 MJ/kg PLA or 17.4% of the GFEU of PLA. The 9.4 MJ is the sum of the gross energy inputs relating to the operating supplies and the waste water treatment (WWT) (0.6 MJ/kg) and the electricity and other fuels used in the CWM (8.8 MJ). It is not anticipated that fossil energy use contributions related to dextrose production will change significantly in the future. Corn wet milling is a mature technology.
- The GFEU estimated to be required for lactic acid production is 26.3 MJ/kg PLA or 49% of the fossil energy used of PLA. The 26.3 MJ is the sum of the gross energy inputs relating to the operating supplies and the waste water treatment (11.4 MJ) and the electricity and other fuels used in the lactic acid facility (14.9 MJ).

- An additional 13.2 MJ/kg PLA or 24% is used for lactide followed by PLA production from lactic acid. The 13.2 MJ is the sum of the gross energy inputs relating to the operating supplies and the waste water treatment (0.4 MJ) and the electricity and other fuels used in the lactide and polylactide production facility (12.8 MJ).

As lactic acid and PLA production cumulatively represent 73% of the GFEU for PLA, these processes are an appropriate target for (energy) efficiency improvements. These processes are rather new and have a high potential for further improvement and resulting energy savings. Further, because of the environmental impacts associated with fossil energy use, improvements in efficiency and/or substitution of conventional energy supplies with renewable energy represent potentially significant opportunities for environmental performance improvements.

7.2. PLA versus petrochemical polymers

Life cycle inventory analysis accounts for all inputs and outputs for a particular product and is typically practiced on a cradle to grave basis. A key benefit of LCA is the opportunity to benchmark performance against competitor products and processes in the marketplace, both to justify performance claims and to identify operations appropriate for performance improvement efforts. This section compares the eco-profile for PLA to industry-generated ecoprofiles for traditional petrochemical polymers of various kinds. Because a wide range of uses and ultimate dispositions (such as chemical and mechanical recycling, incineration and composting) are possible for polymer pellets, this analysis truncates the traditional cradle-to-grave analysis to a more comparable cradle-to-polymer pellet baseline. The cradle-to-pellet ecoprofile comparison is most valuable and accurate as long as the quantity of polymer required for an application and the end fate of the polymer are similar. Of course, in reality, quantities of PLA and the polymers it potentially replaces in applications do vary in the mass required. However, on average the mass of PLA required is similar to the polymer it replaces and the disposal options practiced are anticipated to be largely the same as those for the polymers replaced. As an example, one of the applications for PLA are bottles for short shelf life milk and vegetable oil packaging. Cargill Dow did together with one of his customers a LCA study comparing PET with PLA bottles. In this case the weight of a PLA bottle was even 6% less compared with the weight of the PET bottle, both having the same function.

Polymers can be compared for a wide range of impact categories. This article focuses on three categories of increasing importance around the world today—fossil energy use, greenhouse gas emissions and water use—in order to illustrate the comparative process, and to emphasize key performance benefits identified for PLA.

The use of fossil energy resources is an important global issue. Petroleum resources are limited and many experts believe that there will be supply disruptions and possible limitations within the next few decades. But an even more important problem with the use of fossil energy is the huge translocation of carbon from the ground into the atmosphere accompanied by emissions of sulfur and nitrogen oxides as well as all kinds of hydrocarbons and heavy metals. Fossil fuels are also the dominant global source of antropogenic greenhouse gases (GHG), rising concentrations of which are widely understood to drive global warming [20], with what a growing majority of the scientific community believes will lead to an unstable and unpredictable climate. Global warming can lead to more frequent and more extreme weather events such as floods, droughts, heat waves, windstorms, icestorms, hurricanes and cyclones. Other negative effects are an increase in air pollution, water and food-borne diseases, the arrival of diseases like malaria, dengue fever and yellow fever, an increase number of wildfires, the loss of land by sea level rising, the forced migrations of people, plants and animals that can result in a serious reduction in the number of species, drop in prosperity and even starvation. Also the OECD qualifies in their report 'Working Together Towards Sustainable Development' [23] climate change as one of the greatest challenges, globally. Even climate change skeptics have expressed support for increased efforts to better understand the issues. More cautious business leaders increasingly view fossil fuel related emissions and global climate change as a key risk parameter, with strong potential to adversely impact long-range business planning goals and objectives. Cargill Dow believes that the interconnected issues of fossil fuel resource consumption, depletion and supply discontinuity, coupled with anthropogenically-induced climate change, constitute the major challenges for humanity this century. As a result, products and services providing equivalent or superior function with little or no resulting GHG emissions will enjoy an increasing global market advantage.

7.3. Fossil energy use

Life cycle assessment provides valuable insight into the way PLA performs environmentally compared to incumbent competitor products. The existing range of petrochemical based plastics is diverse, specialized and mature, so that precise and exact comparisons with PLA, a single product performing multiple functions, are difficult, especially considering the great number of impact categories compared. Again, because of the importance of fossil energy use to the environment, a comparison of fossil energy use among a wide variety of

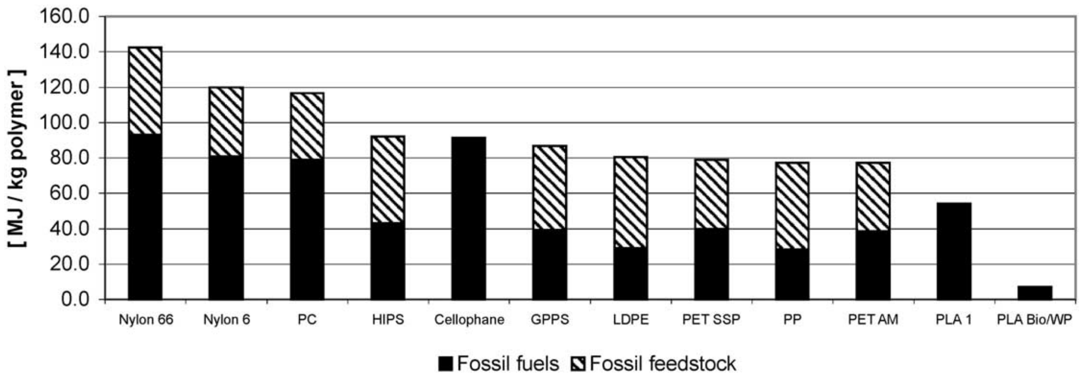


Fig. 8. Fossil energy requirement for some petroleum based polymers and polylactide. The cross-hashed part of the bars represent the fossil energy used as chemical feedstock (the fossil resource to build the polymer chain). The solid part of each bar represents the gross fossil energy use for the fuels and operations supplies used to drive the production processes. PC = polycarbonate; HIPS = high impact polystyrene; GPPS = general purpose polystyrene; LDPE = low density polyethylene; PET SSP = polyethylene terepthalate, solid state polymerisation (bottle grade); PP = polypropylene; PET AM = polyethylene terepthalate, amorphous (fibers and film grade); PLA1 = polylactide (first generation); PLA B/WP (polylactide, biomass/wind power scenario).

petroleum-based polymers against the two previously described polylactide cases is illustrative of key differences between the product types. Fig. 8 plots the fossil energy requirement for these products. Data for the petroleum-based polymers was supplied by the Association of Plastics Manufacturers in Europe (APME). The data is valid for the polymers as produced in Europe. A key finding of the analysis is that the first generation Polylactide production system (PLA1) uses 25–55% less fossil energy than the petroleum-based polymers. With the process improvements targeted by Cargill Dow for the near future (PLA B/WP) the use of fossil energy can be reduced by more than 90% compared to any of the petroleum-based polymers being replaced. This also will give a significant reduction in fossil energy related air and water emissions. This comparison represents the outstanding potential for environmental benefits for polymers made from renewable resources.

It must be remembered that the data for PLA1 and PLA B/WP represent engineering estimates. In addition, there is good reason to expect improvements in the actual performance versus the estimates. Despite years of development work, the commercial manufacturing process for PLA is in its infancy. If the experience from petrochemical-based polymers offers any instruction, it is that process improvements implemented in the early years of a technology typically lead to substantial cost improvements. This is because the pursuit of cost improvements for competitive reasons often targets energy use due to its relatively high contribution to overall material costs. For example, Cargill Dow engineers are already at work on biocatalyst and lactic acid manufacturing process improvements that should further improve the performance at the Blair facility (PLA1) and simultaneously reduce energy demand. There is therefore good reason to expect a performance improvement trajectory for PLA1 that mirrors the experience from the current incumbent materials.

In addition, and as explained above, Cargill Dow has identified the even larger fossil energy use improvements available from a strategy of shifting to biomass feedstocks. The key improvements associated with biomass feedstock technology stem from the use of the lignin fraction of the raw material to displace fossil-fuel based energy requirements, and the resulting improved economic opportunity to rely on renewable energy (wind) for the balance of facility power needs [21].

As described above, life cycle assessment offers value to operational strategy development by identifying actions that contribute both to cost and environmental performance improvements. For a company seeking to maximize economic, social and environmental sustainability, a strategy objective of efficiency improvements and elimination of fossil fuel use improves performance and sustainability against all three elements of the ‘‘triple bottom line.’’

7.4. Global climate change

Global climate change has been identified as perhaps the most important environmental issue of this century. Greenhouse gas emissions are not exactly the same as combusted fossil fuel emissions, because several non-combustion gases can contribute to global climate change. For example, methane (CH_4) is a potent greenhouse gas that can emanate from natural gas system leaks, decomposition of biological materials, and chemical/industrial processes. However, greenhouse gas emissions are closely correlated to fossil fuel emissions because combustion of fossil fuels is the source of most anthropogenic greenhouse gases. Cargill Dow has undertaken a comparison of the contributions to global

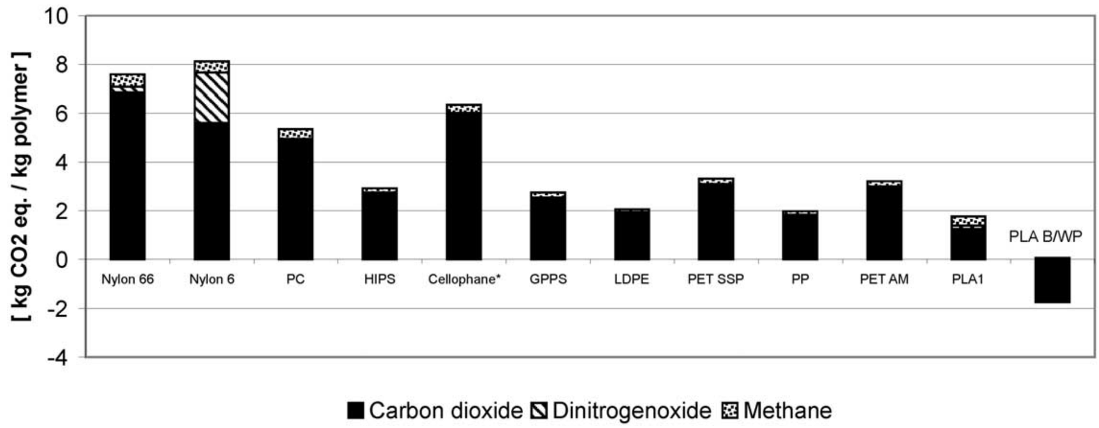


Fig. 9. Contributions to global climate change for some petrochemical polymers and the two polylactide polymers. PC = polycarbonate; HIPS = high impact polystyrene; GPPS = general purpose polystyrene; LDPE = low density polyethylene; PET SSP = polyethylene terepthalate, solid state polymerisation (bottle grade); PP = polypropylene; PET AM = polyethylene terepthalate, amorphous (fibers and film grade); PLA1 = polylactide (first generation); PLA B/WP (polylactide, biomass/wind power scenario).

climate change from a range of petrochemical-based polymers as well as the two PLA cases described above. This comparison is depicted in Fig. 9.

In conducting this analysis, Cargill Dow relied upon the 100-year time horizon Global Warming Potentials for greenhouse gases, a time period generally accepted as the mean atmospheric residence time for the most volumetrically significant greenhouse gas, carbon dioxide. A check of the data revealed that use of the 20 and 500 year time horizons generates the same ranking among the products studied. According to the Intergovernmental Panel on Climate Change (IPCC) the relative global warming potentials of the three largest (volumetric) greenhouse gases are: CO_2—1; CH_4—21, and N_2O—310 [22]. These factors were used in Cargill Dow's analysis. As in the comparison of fossil energy use, the analysis compares conventional polymers with PLA from cradle to pellet (from raw materials to the point where the product is ready for shipment to a converter or fabricator). All emissions values were converted to CO_2 equivalents in order to facilitate comparison.

The analysis demonstrates that the PLA1 production process enjoys a substantial advantage over most polymers, and is comparable to several others. Even more exciting are the greenhouse benefits that derive from the transition to corn residue (lignin fraction) and reliance on wind energy for the balance of plant energy requirements. The utilization of the lignin fraction of lignocellulosic feedstocks for process heat generation ''closes the loop'' on carbon related to energy generation, and in combination with other factors yields a negative greenhouse gas impact for PLA pellets. A most appealing result of the use of agricultural feedstocks for the PLA polymer production and most of the process energy requirement means that customers using PLA

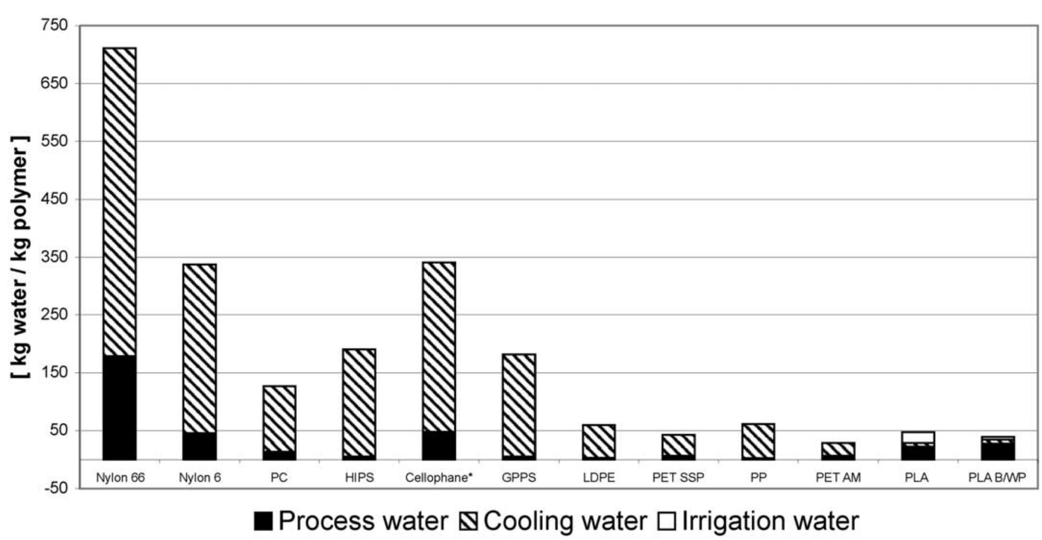


Fig. 10. Gross water use by petrochemical polymers and the two PLA cases.

can not only use PLA as a product, but as a component of their greenhouse gas reduction strategies.

Life cycle assessment reveals that no petroleum-derived polymer can rival the greenhouse gas sink effect of the improved PLA process. Although disposal of PLA products—whether by combustion, composting or other conventional means—results in a return of carbon dioxide to the atmosphere, this advantage survives. In addition, the fact that PLA can be chemically recycled into new feedstock with the proper recovery and processing infrastructure offers the unique opportunity to permanently close the loop on carbon emissions related to the product and to permanently sequester carbon dioxide into a product that is constantly renewed.

7.5. Water use

A third impact category investigated is gross water use. Fig. 10 gives the gross water use of the traditional polymers and the two PLA cases as described above. The gross water use is the sum of public supply, river, canal, sea and well water and used as cooling water, process water and irrigation water.

Despite of the use of irrigation water during corn growing and the two water-based processes (dextrose and lactic acid production) the total amount of water required is competitive with the best performing petrochemical polymers.

7.6. Potential reductions in the fossil energy use of polylactide

As summarized above, the potential for fossil energy use reductions from a PLA production platform shift to biomass feedstocks and renewable energy inputs is quite large. Another useful feature of detailed life cycle assessment is the ability to disaggregate category impacts according to their technological and process drivers. Moreover, because of the relationship between fossil energy use and several other important environmental criteria associated with related air, water, and solid waste emissions, more detailed analysis of impact drivers allows fine-grained thinking about process improvements offering the greatest environmental benefit compared to investment or operational costs. Fig. 11 re-cumulates the disaggregated benefits associated with key process improvements incorporated in the PLA B/WP platform according to three constituent components: lactic acid conversion technology improvements, benefits associated with use of lignocellulosic biomass feedstocks and the use of wind power to meet the remaining electricity input requirements.

In Fig. 11, process and technology improvements are compared against the current process (PLA1) which relies on conversion of corn starch into polylactide.

1. Lactic acid production technology improvements. The reduction in GFEU of 5.3 MJ/kg PLA is the result of replacing the current lactic acid production technology by the future one in the PLA1 production chain. This reduction is caused by reductions in the use of several operating supplies (and concomitant reductions in solid waste) and steam balanced against an increase in sugar and electricity demand. This demonstrates another important value of LCA—the ability to analyze and validate process improvements against a measure of net category impacts.
2. The third column gives the GFEU of PLA using a biorefinery for sugar and steam production combined with the future production technology for lactic acid. The required electricity is coming from the public grid. This production system gives a potential reduction of 24.9 MJ/kg PLA compared with PLA1. The introduction of only a biorefinery into the system leads to a reduction of about 19.6 MJ/kg PLA. The biomass refinery utilizes under this analysis corn stover (stalks and husks not required for soil nutrient management)

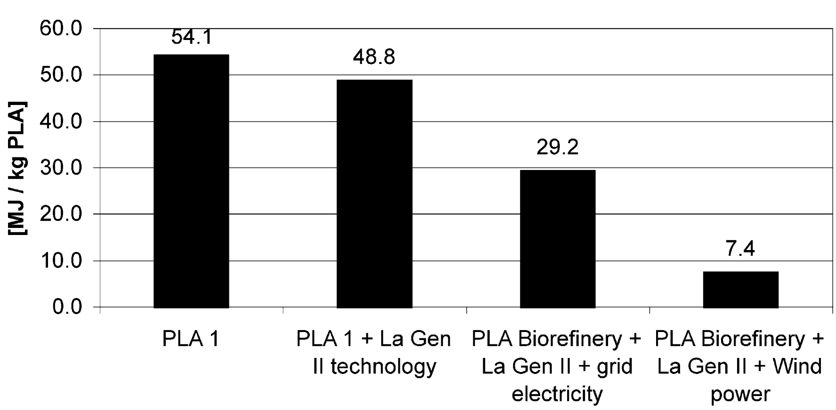


Fig. 11. Potential reduction of gross fossil energy use (GFEU) in PLA production.

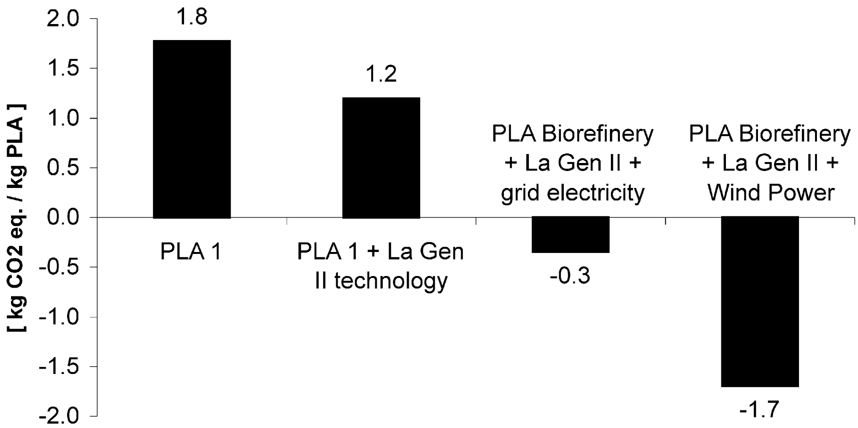


Fig. 12. Potential reduction of greenhouse gasses associated with PLA production.

and is a major source of fossil energy use reductions. Using the lignin fraction of biomass feedstocks as a thermal energy source (via conversion of lignin by combustion or gasification) reduces the fossil energy use. In this model the lignin rich fraction is combusted to produce the steam.

3. Wind power. The effect of the introduction of wind power is calculated by replacing grid electricity by wind power in the biorefinery, lactic acid and polylactide production facilities of the PLA B/WP production chain. This option gives an additional reduction of 21.8 MJ/kg PLA. The GFEU of PLA B/WP is 7.4 MJ/kg PLA. Another important effect of the use of wind power is the significant reduction in air emissions contributing to among others global warming, acidification and toxicity. Although wind power could be relatively expensive in the first generation (PLA1) production system, it is a more economically attractive option under PLA B/WP by the step-wise approach of reducing demand through process energy efficiency improvements and deriving useful energy from the lignocellulosic feedstock. This makes it more affordable to supply the remaining plant's electricity needs by wind power.
4. Energy reductions by process efficiency improvements of the lactide and polylactide facilities are not included.

After Cargill Dow has fully implemented these technology improvements and changes, the residual fossil energy use is about 7 MJ/kg PLA. This remainder is attributable to upstream inputs, including transportation, fertilizer, pesticides, and other raw materials. The final component of Cargill Dow's journey to sustainability will lie in targeting these residual impacts through the participation in processes to develop and apply a sustainable agricultural products standard for agricultural inputs to these farm-driven impacts.

7.7. Potential reductions in greenhouse gas emissions associated with polylactide

In the same manner that Cargill Dow studied the component impacts on fossil energy use for improvements in technology and processes, impact of these measures on greenhouse gas emissions was also analyzed, disaggregated and re-cumulated. Fig. 12 depicts the results of this analysis, again compared to the baseline of current PLA production processes (PLA1).

1. Lactic acid production technology improvements: the introduction of an improved lactic acid production technology is expected to yield greenhouse gas emissions reductions of 0.58 kg CO_2 equivalents per kilogram of PLA pellets (CO_2-eq./kg PLA). This reduction in emissions represents the net benefit of operating supplies and steam reductions and an increased use of sugar and electricity as discussed above.
2. The third column gives the greenhouse gas emissions of PLA using a biorefinery for sugar and steam production combined with the future production technology for lactic acid. The required electricity is coming from the public grid. This system give a reduction of 2.1 kg CO_2-eq./kg PLA compared with PLA1.
3. Wind power. The effect of the introduction of wind power is calculated by replacing grid electricity by wind power in the biorefinery, lactic acid and polylactide production facilities of the PLA B/WP production chain. This option gives an additional reduction 1.35 CO_2-eq./kg PLA.

The cumulative potential impact of these measures is approximately 3.5 kg CO_2-eq./kg PLA, and the resulting target for PLA B/WP greenhouse gas emissions performance improvements is −1.7 kg CO_2-eq./kg PLA. Again, a full cradle-to-grave LCI will be impacted by the ultimate disposal fate of the PLA product, with the greatest potential benefit stemming from recycling of waste PLA into new feedstock. Initial analysis suggests that landfilled PLA will probably remain a slight CO_2 sink, while net greenhouse gas emissions for composted or incinerated PLA B/WP products will be slightly positive.

8. Conclusions

Cargill Dow is learning to use life cycle inventory data in much the same way that process economic data is utilized—to target and improve key process components [21]. As such LCA has become a valuable complementary analytical tool when married with the pursuit of cost improvements, and helps move the company toward its goal of sustainability in process and operations. Moreover, the analysis increasingly demonstrates that the best cost or environmental performance improvement tactics and strategies yield multiple benefits, all of which are valuable to the company as it seeks commercial market success.

Most fossil resource-based polymer production technologies such as for polystyrene, polyethylene and polyethylene terephthalate have reached maturity over the many years that they have been in the marketplace, and processes have been largely optimized. As a new polymer, NatureWorks™ PLA offers the best promise for continued improvement against current performance characteristics. These improvements will ultimately be derived from a mix of materials, process and volume improvements, and represent a key difference between PLA and conventional materials that is relatively difficult to capture in ''snap shot'' life cycle analyses. Still, comparison against established LCA data and protocols for incumbent products does yield understanding sufficient upon which to substantiate performance claims and to guide efforts at environmental performance improvements. LCA provides a valuable basis for benchmarking performance in competitive markets.

Increasing reliance on LCA and the growing import of environmental considerations means that materials and chemicals from renewable resources must demonstrate at least comparable and preferably superior environmental performance as a condition of successful market entry. Two key attributes, for which reliable data exists for conducting such analysis, and of growing public and regulatory concern, are fossil energy use and greenhouse gas emissions. Superior performance in these areas is a vital concern due at least in part to the relatively large fossil energy and greenhouse gas footprints for conventional petrochemical-based polymers. This driver of environmental performance marks a significant shift away from emphasis on biodegradability, the issue which dominated concern about renewable resource-based polymers just 10 years ago, and may well be a function of the increasingly common practice of using LCA as an evaluation tool.

Lower fossil energy use and reduced greenhouse gas emissions are also increasingly correlated with cost competitiveness. This is a direct result of the relatively high process energy use associated with polymer production systems of all kinds. Although PLA production systems generally outperform traditional petrochemical-based polymers in these key impact categories, continued improvements in the energy-intensive processing systems associated with PLA also constitutes an important cost reduction strategy. LCA is therefore an increasingly important tool in identifying and validating cost performance improvement activities. Far from being an obscure technique unrelated to more ''important'' operational concerns, LCA is an integral component of business operations in markets that increasingly reward more sustainable performance.

The magnitude of the contribution of energy use (and related greenhouse gas emissions) to the overall ecoprofile for PLA implies a long-term strategic commitment to continuous improvement as an indicator of a commitment to environmental sustainability. In some cases, as with Cargill Dow's plans to shift from a starch to a biomass platform for lactic acid production, this commitment in turn implies strategic process development objectives. Again, actions to dramatically improve the ecoprofile are often rewarded with dramatic cost improvements, as is the case when shifting from feed corn to corn residue. The good news for innovative and relatively immature technologies like PLA is that history instructs that process efficiency and cost improvements typically accompany full commercialization. Another benefit of LCA is that it is a process that facilitates the tracking of these improvements with reasonable detail and precision.

Polymers from renewable resources can be signficantly lower in greenhouse gas emissions and fossil energy use today as compared with conventional petrochemical-based polymers. Over the longer term, LCA demonstrates that PLA production processes can become both fossil-energy free and a source of carbon credits. This bright future will come only with significant investment of time, effort and money. A final, important benefit of LCA is that it can serve as a tool for monitoring return on these investments over time.

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