The eco-profiles for current and near-future NatureWorks® polylactide (PLA) production

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Nomenclature

CO_2 eq.	Carbon dioxide equivalents
CWM	Corn wet mill
GHG(s)	Greenhouse gas(es)
LCA	life cycle assessment/analysis
LCI	Life cycle inventory
MAPP	Mid-Continent Area Power Pool
MWh	Megawatt-hours
REC	Renewable energy certificates
OPPD	Omaha Public Power District
PET	Polyethylene terephtalate
PLA	Polylactide; here, refers to NatureWorks' polymer
PLA5	2005 PLA production system
PLA6	2006 PLA production system
PLA/NG	Next-generation PLA production system
PS	Polystyrene
PP	Polypropylene
t	tonne = metric ton
WP	Wind power
WWT	Waste water treatment
WWTP	Waste water treatment plant

Keywords: *NatureWorks, polylactic acid, polylactide, PLA, life cycle assessment, life cycle analysis, eco-profile, wind energy, renewable energy certificates*

Abstract

NatureWorks® polylactide (PLA) is a versatile polymer made entirely from annually renewable resources. Within the framework of sustainability, NatureWorks LLC is working to continuously improve the environmental performance of its product portfolio and is using life cycle assessment as a tool to identify and measure environmental performance-improvement objectives and to benchmark PLA against the petroleum-based polymers with which it competes in the marketplace. NatureWorks' objectives include eliminating non-renewable energy use and the emissions of greenhouse gases (GHGs), as well as minimizing non-valuable co-products and reducing water use. These objectives are accomplished through continual improvement of the PLA production technology and utilization of renewable energy for process energy as much as possible. NatureWorks is purchasing wind power-derived renewable energy certificates (RECs) in an amount equal to the electricity used in the PLA production system in a commitment to utilize renewable energy wherever possible. The use of renewable wind energy certificates reduces the environmental burden associated with electricity use. The PLA production system in 2006 emitted 0.27 kg CO_2 eq./kg PLA and used 27.2 MJ/kg PLA of fossil energy—reductions of 85% and 50%, respectively, compared to 2003 PLA eco-profile data. In the near future, further improvement of the process technology,

combined with the utilization of wind power for the process electricity requirements, will make NatureWorks PLA pellets a GHG sink. This paper provides the cradle-to-polymer-factory-gate life cycle inventory data (eco-profiles) for the 2006 and the near-future PLA production systems and explains the use of RECs.

1. Introduction

In 2003 NatureWorks® LLC published the life cycle assessment of NatureWorks PLA production[1]. That paper gave an introduction to the company NatureWorks (formerly Cargill Dow LLC), PLA production technology and applications and the life cycle assessment (LCA) tool as applied to PLA. Further, the paper discussed how the cradle-to-factory-gate inventory data (often called the eco-profile) was calculated and used in two applications: benchmarking against petroleum-based polymers used for the same applications as PLA, and tracking PLA production process improvements. The 2003 data was based on the plant design. NatureWorks now has actual data available from its production facilities in addition to newer data for the upstream and supporting processes, providing a good basis for updating the PLA cradle-to-factory-gate inventory (eco-profile). Additionally, NatureWorks is purchasing RECs based on wind power, reducing the PLA environmental footprint. Up-to-date life cycle inventory (LCI) data is needed by users (converters, retailers, and brand owners) and authorities to provide better insight into the performance of the PLA production system and to allow comparison with the petrochemical-based polymers that PLA replaces in the marketplace. The objectives of this paper are to provide detailed inventory data sufficient for use by LCA practitioners interested in the use of PLA resin for specific products and to show the effects of the utilization of wind energy and future developments in PLA production. The acronym "PLA" used in the context of this study refers only to the NatureWorks® polylactide polymer.

In November 2001, NatureWorks started the production of PLA in its 140,000-tonne-per-year manufacturing facility in Blair, Nebraska. One year later, NatureWorks started producing lactic acid in its 180,000-tonne-per-year manufacturing facility located next to the polymer plant. Today, these two plants are the only large-scale commercial production facilities for PLA worldwide. The production of PLA is still in its infancy compared with that of traditional polymers, and there is great potential to further reduce its cost and environmental footprint.

This paper describes and assesses the life cycle performance of the following PLA production systems:

1. **PLA6:** This case represents 2006 cradle-to-pellet PLA production system as described in Section 2, including purchasing wind-based RECs to offset the environmental burden of the electricity used in the PLA production system, with the environmental burden of electricity produced by windmills.

2. **NEXT-GENERATION PLA PRODUCTION SYSTEM (PLA/NG):** This case represents the future or next-generation (NG) cradle-to-pellet PLA production system. This production system is expected to reduce the environmental footprint of PLA via the implementation of new process technology. The new process technology will reduce energy, raw material use, and co-product creation. Green power (defined in Section 3.6) is expected to be used to supply electricity in the Cargill/NatureWorks controlled production processes. The biobased feedstock (maize/corn), the minimization of direct GHG emissions through process improvements, and the replacement of grid electricity with green power will make the cradle-to-factory-gate PLA/NG pellets a GHG sink.

The data provided in this report represents an annual production of 140,000 tonnes (t) and is valid from the cradle to the polymer factory (exit) gate in Blair, Nebraska. Additional eco-profile data for shipment to Europe and Asia are provided on the NatureWorks website[2].

2. Description of the PLA production system

Figure 1 shows the simplified flow diagram and system boundary for the NatureWorks PLA production system. The cradle-to-factory-gate PLA production system is divided into five major steps:

1. Corn production and transport of corn to the corn processing wet mill
2. Corn processing and the conversion of starch into dextrose
3. Conversion of dextrose into lactic acid
4. Conversion of lactic acid into lactide
5. Polymerization of lactide into polylactide polymer pellets

The life cycle of PLA starts with corn (maize) production. All free energy consumed by the corn plant comes from solar energy captured by photosynthesis. The basic stoichiometric equation for photosynthesis is:

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

In this equation, (CH_2O) represents carbohydrate, such as sucrose and starch. Therefore all carbon, hydrogen, and oxygen found in the starch molecule or the final polylactide molecule originated from water and carbon dioxide.

The eco-profile of PLA includes all the relevant inputs for corn production such as production of corn seed, fertilizers, limestone, electricity, and fuels (natural gas, diesel, propane, and gasoline) used on the farm, the atmospheric carbon dioxide utilization through photosynthesis, the irrigation water applied to the cornfield, and the production of the herbicides and insecticides used to grow the corn. On the output side, emissions including dinitrogen oxide, nitrogen oxides, nitrates, and phosphates are taken into account. Production of the farm equipment (tractors and harvest combines) used was investigated, but their contributions are negligible[3].

After harvest, the corn grain is transported to a corn wet mill (CWM), where the starch is separated from the other components of the corn kernel (proteins, fats, fibers, ash, and water) and hydrolyzed to dextrose using enzymes. The dextrose solution is transported by pipeline to NatureWorks' fermentation process, which is situated adjacent to the CWM. The other products of the modeled CWM are corn gluten feed, corn gluten meal, and corn germ. The eco-profile of PLA includes all relevant inputs for dextrose production such as the production and delivery of natural gas, electricity, and steam con-

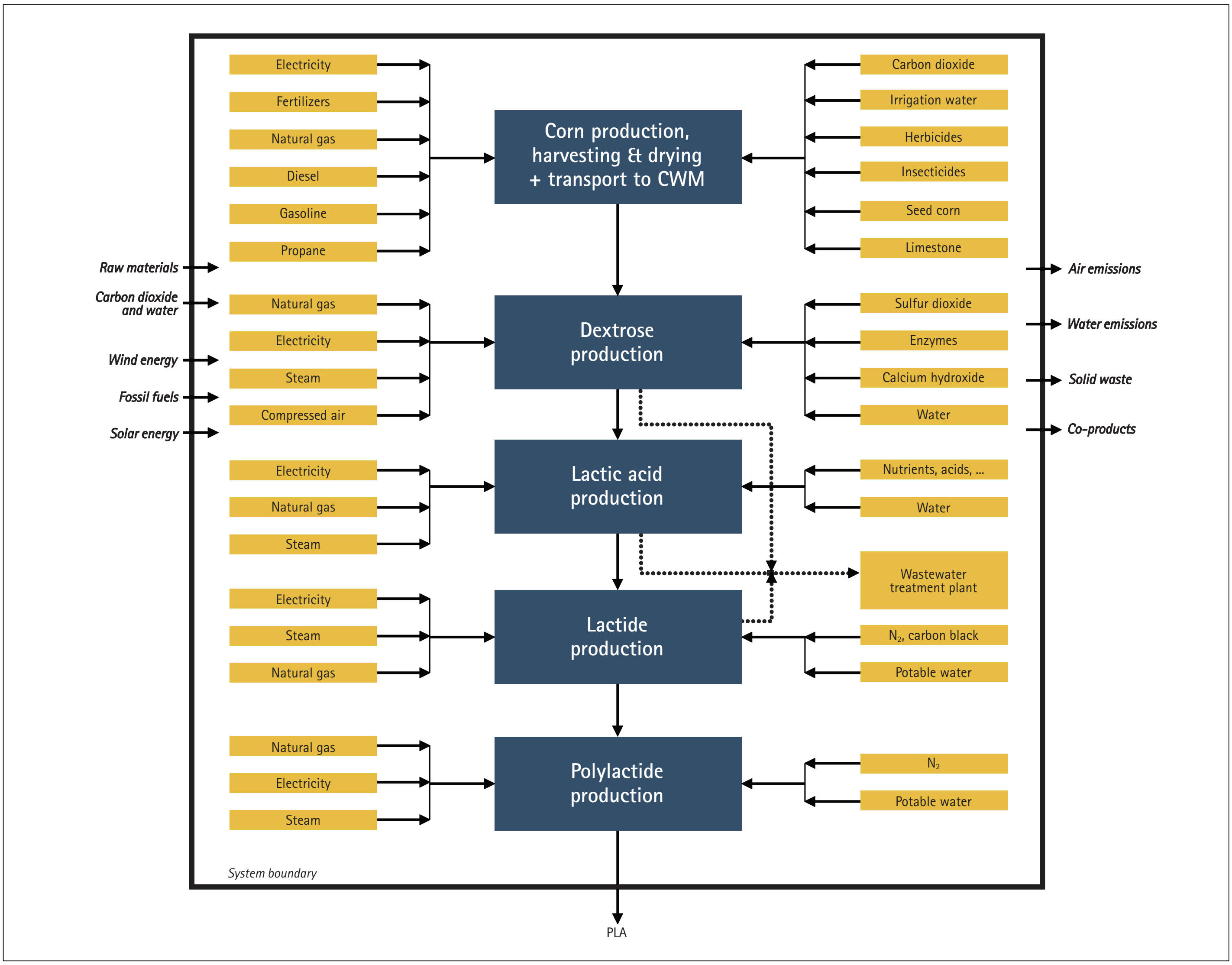

Figure 1. Simplified flow diagram and system boundary for the NatureWorks PLA production system

sumed, as well as the production of potable and cooling water, compressed air, chemicals (sulfur dioxide and calcium hydroxide), and enzymes[4].

Lactic acid is produced by fermentation of dextrose received from the CWM. The process, illustrated in *Figure 2*, combines dextrose and other media, adds a microbial inoculum, and produces crude lactic acid whose pH is controlled by the addition of calcium hydroxide. The lactic acid broth is then acidified by adding sulfuric acid, resulting in the formation and precipitation of gypsum. Gypsum is removed by filtration, and the lactic acid is concentrated by evaporation. After final purification, the lactic acid enters the lactide/PLA process.

NatureWorks PLA is prepared through the polymerization of lactide to make polylactide polymer. NatureWorks' process, illustrated in *Figure 3*, is a continuous process. In the first step, water is removed in a continuous condensation reaction of aqueous lactic acid to produce low-molecular-weight prepolymer. Next, the prepolymer is catalytically converted into the cyclic dimer, lactide. The molten lactide mixture is then purified by distillation. Finally, high-molecular-weight PLA polymer is produced using a ring-opening lactide polymerization. NatureWorks process does not use solvents. After the polymerization is complete, any remaining lactide monomer is removed and recycled within the process[1,5].

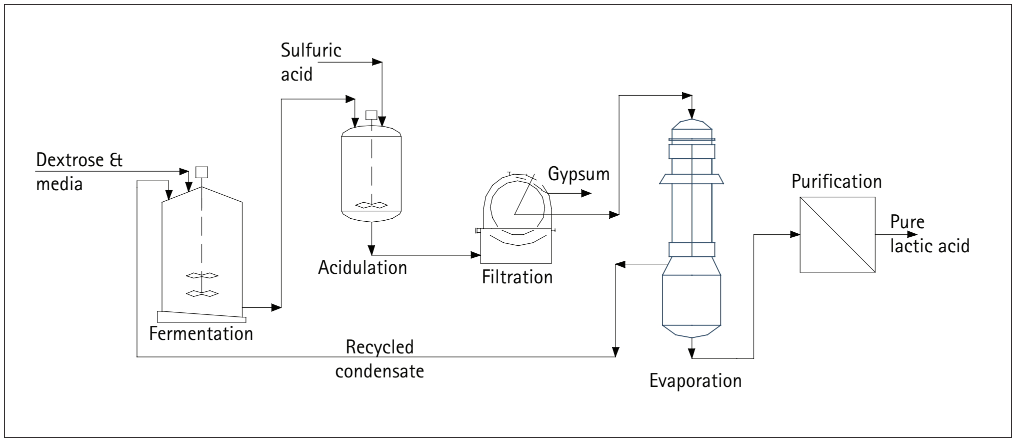

Figure 2. NatureWorks lactic acid production process

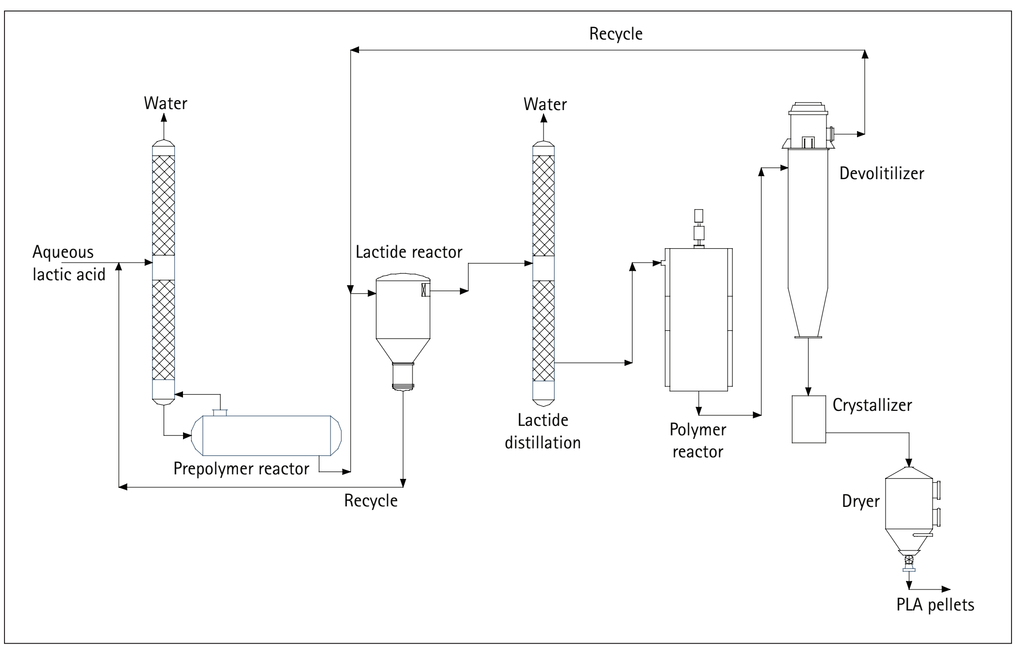

Figure 3. NatureWorks lactide formation and polylactide polymerization process

The eco-profile of PLA includes all relevant inputs used in PLA production, including natural gas, electricity, steam, potable and cooling water, nitrogen, and chemicals. The eco-profile traces all of the inputs back to the extraction of the raw materials from the Earth. Also included are the process emissions of the CWM, fermentation, and the polymerization process as well as the electricity consumption and the process emissions (to air and water) of the facility treating the waste water from PLA manufacture. The polymer pellets are the final stage of the PLA eco-profiles. Packaging and transportation to the customer are not included. The LCA model utilizes detailed input

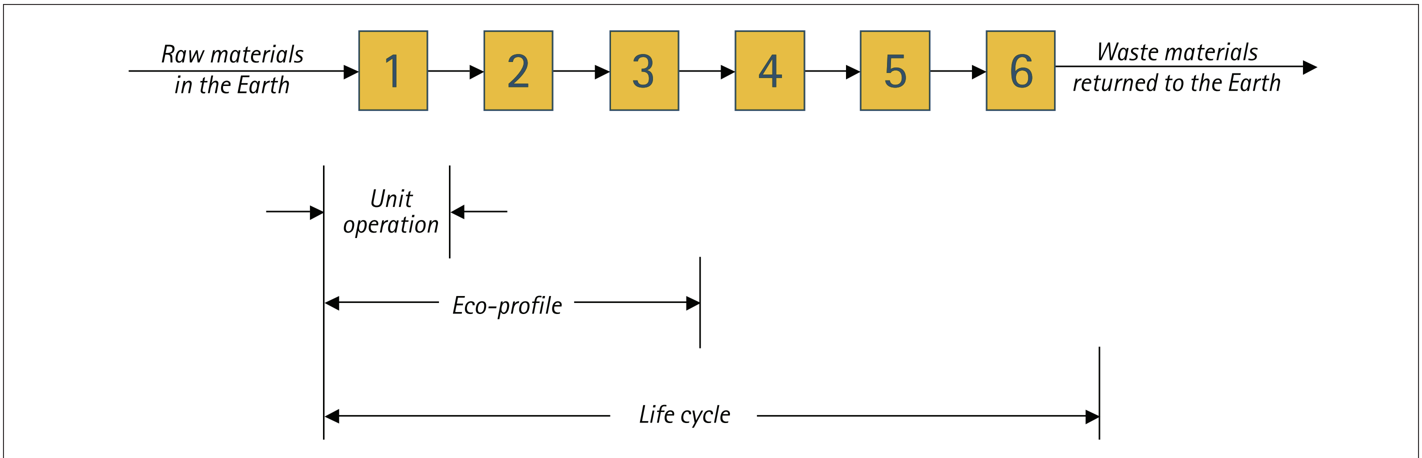

Figure 4. The difference between eco-profiles and life cycles

data to generate the eco-profile. To protect the intellectual property value of NatureWorks' proprietary technology, not all details of every input or output are shared here.

3. Methods

3.1. ECO-PROFILES & LIFE CYCLE INVENTORIES

A full life cycle inventory analysis, sometimes referred to as a cradle-to-grave analysis, starts with raw materials in the Earth and covers all downstream processing and use operations until the materials are eventually disposed of as waste back into the Earth. Eco-profiles, of the type reported by Plastics*Europe* and NatureWorks, are cradle-to-gate rather than life cycle inventory analyses; that is, the systems start with raw materials in the Earth and end with polymer resins ready for dispatch to the converter. This difference is illustrated in *Figure 4*. *Figure 4* supposes that a processing sequence contains six operations and takes raw materials from the Earth, processes them, and eventually returns them as waste back into the Earth. A full life cycle inventory analysis encompasses all of these six operations, as shown. In contrast, if we suppose that operations 1 to 3 are needed to produce a polymer resin, then the eco-profile will encompass only operations 1 to 3[6]. The eco-profile of PLA gives the total or cumulative energy use, raw material use, air and water emissions, and solid waste produced from the cradle to the PLA polymer factory (exit) gate.

3.2. METHODOLOGY

As a renewably derived source of plastics, PLA competes directly in the marketplace with polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), and other petrochemical-based plastics often referred to as "traditional" plastics. Because of customer demand, Plastics*Europe* has published a series of eco-profiles for traditional petrochemical-based polymers over the last fifteen years[7]. To allow direct comparison with the traditional polymers, NatureWorks undertook the development of eco-profiles for PLA using the same methodology[6], software, and core databases[8] as used in the Plastics*Europe* analyses. In addition, the results are presented in the same format used by Boustead Consulting, the organization that calculated these eco-profiles for the European plastics industry.

3.3. DATA SOURCES

NatureWorks' development of PLA eco-profiles, as well as the harmonization of these eco-profiles with the Plastics*Europe* methodology, has required new data and analysis, as well as engineering estimates. Average corn-growing data from Nebraska and Iowa (the most likely sources of corn for the Cargill CWM) was collected and used for the corn production eco-profile[3]. Data for a modern CWM representative of the Cargill CWM that supplies NatureWorks was compiled and used for the dextrose production step[4]. Data for the lactic acid, lactide, and polylactide production was developed within NatureWorks. The fossil-fuel-based electricity data was obtained from the Boustead Core database and valid for the Mid Continent Power Pool (MAPP) covering the US states North and South Dakota, Nebraska, Minnesota, and east Wisconsin. The wind energy production data was taken from a peer-reviewed LCA on wind power[9], and the data for the most important process chemicals was obtained from direct suppliers whenever possible or taken from the Eco-invent database[10]. Data for the production of coal, gas, and other fuels and chemicals used in smaller quantities was taken from the core database of the Boustead model[8]. All data sources, including corn growing, corn milling, lactic acid, lactide, and polylactide production data, were peer-reviewed by Ian Boustead[11].

3.4. IMPROVEMENTS OF THE PLA PRODUCTION SYSTEM

On a global basis, the emissions of greenhouse gases and the use of fossil energy are key sustainability measurements for products. They are key indicators because both have a global impact. Therefore, both are targets for NatureWorks as it aims to reduce the impact of PLA production on the environment. Producing PLA from renewable resources still requires a significant use of non-renewable fuels (mainly gas and coal and to a lesser extend oil and nuclear power) and an associated net release of GHG. Closer inspection of the inventory data reveals that the majority of the fuel use and GHG release is associated with the production of process energy, either from the production of steam or from the production of electricity. This process energy is used in corn growing, dextrose production, lactic acid manufacture, and polymer production. It includes the energy needed to run pumps, evaporators, distillation columns, and other process equipment. Basically there are two options to reduce the use of fossil energy and GHG emissions in the PLA production system:

1. Improvements in the Cargill/NatureWorks controlled or internal processes such as the CWM, fermentation, lactide, and polymerization process
2. Improvements in the external processes such as the production of corn, raw materials, and electricity

NatureWorks is improving the eco-profile of PLA through both of the above options. Option 1 can be split up into process and energy efficiency improvements. Both are a direct method of reducing process energy-associated emissions. NatureWorks PLA production technology is in its infancy, at less than 5 years of manufacturing experience in one commercial facility, and as such, has not been optimized through research and operating experience. During this period, NatureWorks gained considerable operating experience and, as a result, identified numerous opportunities to simplify operations, save energy, and increase yield. Throughout process industries it has become a truism that "negawatts" (i.e., energy savings gained by installing energy-efficiency measures) are generally the best first tool for reducing emissions; that is, reducing consumption of energy is the first step in making a more sustainable product. Energy efficiency improvements have the multiple benefits of reducing demand on strained infrastructure, reducing emissions, and reducing energy costs.

With the multiple eco-profile improvement objectives being to reduce PLA production costs and simplify operations, the next generation of PLA technology is in sight. The PLA/NG includes the continued use of renewable electricity to power the facility. It also includes process technology improvements that reduce lime and sulfuric acid use, energy use, solid waste production, and water consumption. While NG technology will show significant improvements in the eco-profile for PLA, additional improvements such as utilization of cellulosic feedstocks are also being considered.

However, even when all of the technically and/or economically achievable energy conservation and process optimization projects have been implemented, there will be a need for power to run the process. Power production is an external process (Option 2). Sections 3.5 and 3.6 will focus on NatureWorks' choice and purchase of renewable electricity to drive the PLA production system. The use of renewable electricity via purchase of RECs is a key improvement from the 2003 eco-profile of PLA.

3.5. MAPPING GHG EMISSIONS USING "THE GREENHOUSE GAS PROTOCOL"

The greenhouse gases carbon dioxide (CO_2), nitrogen oxide (N_2O), and methane (CH_4) are emitted in the four major production steps of the PLA production system: corn (maize) production, corn milling, fermentation, and polymerization. GHGs are also emitted during the production and delivery of many raw materials and operating inputs such as fuels, fertilizers, water, electricity, and acids, as well as other processes such as waste water treatment. Various sources for GHG emissions can be identified: GHGs emitted during the production (process and fugitive emissions) and use (combustion) of fuels and electricity (CO_2 and CH_4), during corn production (fertilizer-related N_2O emission), during the production of required chemicals (CO_2 emissions during the production of calcium hydroxide), and during fermentation (CO_2 emissions from organic and inorganic sources). These GHG emissions result in increased concentrations in the atmosphere, contributing to climate change[12,13]. One of the key advantages of using a renewable feedstock is that annually renewable resources take carbon dioxide from the atmosphere, reducing the impact of gases emitted in other parts of the production system. Electricity-related GHG emissions can be reduced via the purchase of wind-derived RECs, as discussed in Section 3.6.

In this section we review *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*[14,15], a reporting tool developed by the World Resources Institute and the World Business Council for Sustainable Development. This standard includes reporting on the Kyoto basket of six gases, including CO_2, CH_4, and N_2O.

The protocol has been used by a large number of companies and has gained wide acceptance. The Greenhouse Gas Protocol is used to develop an inventory of GHG emissions across an entire business enterprise. The emissions are grouped in three levels:

- Scope 1, which accounts for *direct* GHG emissions from sources that are owned or controlled by the reporting company. In the case of NatureWorks, these emissions are dominated by the generation of steam and hot oil.
- Scope 2, which includes the *indirect* GHG emissions associated with purchase of electricity, heat, or steam generated by an outside party. In the case of NatureWorks, only the externally produced electricity falls within this scope.
- Scope 3, which includes *indirect* emissions that are a consequence of the activities of the reporting company, but occur from sources owned or controlled by another company such as transportation of products, production of raw material, and outsourced manufacturing and waste treatment. Additionally, the sale or purchase of emissions reductions credits to/from outside parties is reported here. In the case of NatureWorks, Scope 3 contains the GHG emissions associated with the production and delivery of operating supplies (e.g., lime and sulfuric acid), feedstock (e.g., corn), fuels (e.g., natural gas), end-of-life operation (e.g., handling of process waste streams), and outsourced activities (e.g., reclamation of operating supplies).

Table 1 shows the rolled-up GHG equivalent emissions for the case of NatureWorks PLA. The data shows that the single-largest source of GHG equivalents is associated with the generation of electricity. This is consistent with data from the US Environmental Protection Agency (EPA), which estimates that more than half of the CO_2 emissions from the U.S. industrial and commercial sectors comes from the use of electricity, generated off-site and supplied through the grid.

Table 1. NatureWorks GHG inventory for the PLA production system grouped as Scope 1, 2, and 3 emissions according to the Greenhouse Gas Protocol

SCOPE		CO_2 eq. (kg/kg PLA)
1	NatureWorks/Cargill site, direct emissions	1.038
2	Indirect emissions from electricity production	1.561
3	Fuel, material, corn production, reclamation	1.244
	Corn feedstock – CO_2 uptake	-1.820
	TOTAL	2.023

Therefore, NatureWorks has investigated the use of renewable energy, particularly wind-generated electricity, to reduce GHG emissions to the lowest possible level in the PLA production system. NatureWorks is also pursuing technology improvement initiatives to further reduce energy and raw material use.

3.6. RENEWABLE ENERGY CERTIFICATES

There are various forms of renewable energy products, including:

- On-site renewable generation, such as installed solar photovoltaic systems and on-site windmills
- Green power, purchasing both electricity and the environmental attributes associated with renewable power generation
- RECs[17]

In general, the different forms are treated differently when reporting emissions. The installation of on-site renewable energy generation, such as photovoltaics and windmills situated on the production site, are incorporated in the Scope 1 GHG emissions. If renewable electricity is offered by a utility company, then green power can be purchased directly, and the Scope 2 emissions are reduced. Finally, RECs can be purchased from qualified suppliers to offset the environmental burden associated with electricity use. These are currently reported as Scope 3 offsets, to the Scope 2 emissions.

What are RECs? Renewable power facilities create more than just electricity. For each megawatt-hour of power from renewable resources in the US, there is one less MWh of power generated from conventional sources such as coal or natural gas. When displacing electricity generated from fossil fuels, renewable power plants reduce the emissions of carbon dioxide, particulate matter, and other pollutants that fossil-fired plants would have emitted. Renewable power facilities thus create two distinct "products":

- Commodity electricity
- A set of environmental attributes

The environmental attributes can be packaged together in a product called a renewable energy certificate. One REC represents ownership of the environmental attributes associated with the generation of one MWh of electricity from new, renewable, non-mandated generation projects. These attributes include the avoided air emissions as well as avoided water emissions, fossil fuels, water consumption, and waste production. In addition to these environmental attributes, each REC also denotes the fuel source, location of generation, and year of generation[16,17,18,19].

A market in RECs has developed over the last few years. The Green Power Market Development Group[20] has played a leading role in fostering standards in this essentially voluntary market. The requirements are aimed at encouraging the development of new green power, precisely because emissions from the current supply of grid-based electricity are the dominant source of emissions for most US companies.

The reason for creating RECs is to economically drive the adoption of renewable energy production. Since renewable energy production is typically more expensive than conventional sources at current fossil energy cost, the sale of RECs can provide the additional revenue to justify the decision to invest in wind electricity production. Certainly not all renewable electricity can generate RECs. Renewable electricity that is mandated by governmental authorities is one example of renewable energy production that does not generate RECs[21].

RECs can be used where good resources for producing the renewable energy are separated from the consumer who wishes to "use" a 100% renewable electricity product. The sale of RECs allows the consumer to use renewable electricity and provides the economic justification for the owner of the wind electricity to invest in wind electricity production.

NatureWorks production is not located on a site with an economically competitive wind resource. Therefore, on-site production of wind energy is not an option. Since Nebraska is a public power state, NatureWorks must purchase its electricity from the local utility, OPPD, which did not have sufficient green power available for NatureWorks in 2006. Therefore, today RECs are the only renewable energy source accessible for NatureWorks. NatureWorks has purchased RECs to replace the Scope 2 and 3 electricity use for PLA. RECs are purchased to offset the emissions associated with the electrical usage, resulting in Scope 3 reductions (See *Table 2*).

Table 2. NatureWorks LLC GHG inventory for the 2005 (PLA5) and 2006 (PLA6) PLA production systems

SCOPE		CO_2 eq. (PLA5) (kg/kg PLA)	CO_2 eq. with RECs (PLA6) (kg/kg PLA)
1	NatureWorks/Cargill site, direct emissions	1.038	1.038
2	Indirect emissions from electricity production	1.561	1.561
3	Fuel, material, corn production, reclamation	1.244	1.244
	Corn feedstock – CO_2 uptake	-1.820	-1.820
	RECs purchased to offset Scope 2 electricity emissions		-1.553
	RECs purchased to offset Scope 3 electricity emissions		-0.197
	TOTAL	2.023	0.272

Through the RECs, NatureWorks can influence and improve the external electricity production infrastructure. The electrical power generator receives a premium for the renewable energy attributes, further encouraging the development of additional renewable energy capacity.

RECs can be contractually separated from their underlying electricity and sold independently from power. As soon as the electricity and RECs are "decoupled," or "unbundled," the electricity from the windmill is no longer emissions-free. The GHG Protocol identifies that Scope 2 emissions (purchased) electricity should be based on the appropriate power pool (MAPP) and not the local utility (OPPD). Through the purchase of RECs, the environmental burden of the electricity used in the PLA production system is offset 1:1, with the environmental benefits linked to RECs from the wind-generated electricity.

RECs should be certified by auditing programs such as Green-e® or EcoPower℠. The Green-e program is a voluntary certification and verification program for renewable energy products administered by the Center for Resource Solutions[22] that assures that wind energy is being produced and delivered to the public grid and that the attributes are being claimed only once. The program includes audits of the source project and tracking of the certificate ownership to ensure that the appropriate standards are being met. Applying this protocol to emissions-trading markets ensures that there is no double-counting and that only one entity is claiming ownership of a reduction credit.

NatureWorks sourced RECs from projects within the same subregion as our major end use, for even further consistency. Electricity generated by wind turbines results in considerably lower environmental burdens than non-renewable-energy-based electricity as produced within the US MAPP power pool[8]. The inventory data for the production of wind energy is based on a peer-reviewed study of wind-power systems business, Vestas[9].

4. Results

4.1. THE ECO-PROFILE FOR THE CURRENT PLA PRODUCTION SYSTEM (PLA6)

The current, 2006, NatureWorks polylactide production system is referred to as "PLA6" and is representative of 2006 PLA production. NatureWorks published a description of PLA production in 2003[1] giving the details of energy consumption, GHG emissions, and water use. Since that time, plant operations have improved and new data has become available and is used in this updated analysis. Key pieces of new data include:

1. More representative and accurate data for corn and dextrose production[3,4]
2. Updated lactic acid, lactide, and polylactide production data from NatureWorks, reflecting optimization of the PLA production process in the pioneer production facility
3. Data from key energy and chemical suppliers to NatureWorks PLA production
4. Latest data from the Boustead core database[8], which is continuously updated and optimized

5. Renewable wind-energy-based electricity replacing electricity from the grid produced by non-renewable fossil and nuclear fuels

The detailed eco-profile data for PLA6 is found in *Sidebar A* (*p. 67*). *Table A.1* gives the gross primary fuels and feedstock for the PLA6 production system. The biomass entry in the Feedstock energy column (24.56 MJ) represents the corn intake. The energy content of corn is 16.3 MJ/kg corn. *Table A.2* shows the energy data expressed as masses of fuels. *Table A.3* shows the demand for water. The entry "Unspecified" in the "Use for processing column" mainly represents the irrigation water use during corn production. *Table A.4* shows the raw material requirements. The bottom entry lists "Land use," which is 1.7 m^2/kg PLA. *Table A.5* shows the solid waste generated. *Table A.6* shows the air emissions and *Table A.7* shows the emissions to water. Finally, *Table A.8* shows the temporary co-products. One part of the gypsum produced is sold for land application. (This co-product is not listed in *Table A.8*.) The land-application gypsum replaced mined gypsum, and therefore a credit is given equal to the avoided gypsum mining. The remaining part of the currently produced gypsum is stored in a dedicated monocell landfill; NatureWorks is investigating other applications such as wallboard, cement kiln, and land remediation. In the longer term (PLA/NG), total gypsum production is planned to be reduced by more than 85% and is expected to be completely used in land application. In order to be conservative, no credits are given for the avoided gypsum mining in the PLA/NG case. The interpretation of these tables is described by Boustead[6].

4.2. THE EFFECTS OF THE USE OF WIND-ENERGY-BASED RECs & NEW PROCESS TECHNOLOGY ON A SERIES OF ENVIRONMENTAL INDICATORS OF THE PLA PRODUCTION SYSTEM

NatureWorks is working to reduce the environmental footprint of PLA manufacture through elimination of non-renewable energy use, reduction in GHG emissions, minimization of water use, and reduced generation of non-valuable co-products. These objectives are accomplished through continual improvement of the PLA production technology and by selecting process energy from renewable sources as much as possible. A major source of environmental impact is the electricity used in the CWM and the lactic acid, lactide, and polylactide production process. Using RECs significantly reduces the PLA environmental footprint. The NatureWorks PLA plant is located in Blair, Nebraska, in the mid-central portion of the United States. This region contains significant amounts of high-quality wind resources and is the site for the development of several new wind farms, especially in northern Nebraska, Minnesota, and Iowa. For 2006 NatureWorks LLC purchased Green-e—certified wind RECs[23]. The wind energy is being generated by Sterling Planet wind farms located in the Great Plains region of the US, which includes Nebraska, South Dakota, North Dakota, Minnesota, and Iowa. As a result of new demand for wind energy, new sites are coming into production. For example, in September 2005, a consortium including OPPD (the local electricity supplier to the Cargill/NatureWorks site in Nebraska) began operating Nebraska's newest and largest wind power facility, located in Ainsworth, Nebraska. The facility consists of 36 wind turbines generating a total of 60 megawatts of electricity[24].

Table 2 contains the NatureWorks GHG inventory for the PLA production system grouped as Scope 1, 2, and 3 emissions after purchasing RECs for electricity use in the Cargill/NatureWorks controlled processes (Scope 2), as well as for electricity use in the Scope 3 processes. Scope 1 gives the direct GHG emissions from the Cargill/NatureWorks-owned processes, primarily from steam and hot oil systems. Scope 2 gives the indirect GHG emissions associated with the electricity used in the Cargill/ NatureWorks-owned processes. This electricity is imported from the public grid. Scope 3 gives, respectively:

- GHGs emitted during the production and delivery of all kinds of fuels and materials delivered to Scope 1 processes.
- GHGs emitted during corn production, including the production and use of fertilizers, pesticides, and fuels by the farmer, including the emissions coming from the cornfield itself.
- GHG emitted during the external processing or reclamation of waste streams generated in Scope 1.
- carbon dioxide harnessed by the corn plant for starch formation. This carbon is finally used to build the PLA polymer chains. The carbon dioxide harnessed to grow the corn plant itself (stem, leaves, and husk) is not included.
- RECs purchased to offset Scope 2 and 3 electricity emissions.

The value of 1.553 kg CO_2 eq./kg PLA is slightly lower than the GHG emitted during fossil-fueled electricity production (1.561 kg CO_2 eq./kg PLA) because small amounts of GHG are also emitted during wind power production[9].

The results of purchasing RECs for Scope 2 and 3 electricity consumption is illustrated in *Figure 5*. "PLA5" represents the PLA production system before the utilization of wind energy in 2006. The gross or total primary fuel required to drive all the processes (within Scope 1, 2, and 3) is 50.8 MJ/kg PLA. The energy content of the delivered fuel "at the operator" in the PLA production system is 30.3 MJ/kg PLA. The energy required to produce and deliver these fuels (the 30.3 MJ) is 18.3 MJ/kg PLA. The energy required for transportation is 1.8 MJ/kg PLA, and the fossil energy used in materials (e.g.,

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Sidebar A. The eco-profile of PLA6

Table A.1. Gross primary fuels and feedstock required to produce 1 kg of PLA6

Fuel type	Fuel production & delivery energy (MJ)	Energy content of delivered fuel (MJ)	Fuel use in transport (MJ)	Feedstock energy (MJ)	Total energy (MJ)
Coal	0.29	0.24	0.01	0.00	0.55
Oil	0.03	3.39	1.59	0.26	5.27
Gas	0.69	21.19	0.07	0.10	22.04
Hydro	0.02	0.00	0.00	0.00	0.02
Nuclear	0.41	0.16	0.00	0.00	0.56
Lignite	0.01	0.00	0.00	0.00	0.01
Wood	0.00	0.00	0.00	0.00	0.00
Sulfur	0.00	0.01	0.00	0.11	0.12
Biomass (solid)	0.00	0.00	0.00	24.56	24.56
Hydrogen	0.00	0.09	0.00	0.00	0.09
Recovered energy	0.00	-1.50	0.00	0.00	-1.50
Unspecified	0.00	0.00	0.00	0.00	0.00
Peat	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00
Wave/tidal	0.00	0.00	0.00	0.00	0.00
Biomass (liquid/gas)	0.00	0.00	0.00	0.00	0.00
Industrial waste	0.00	0.00	0.00	0.00	0.00
Municipal Waste	0.00	0.00	0.00	0.00	0.00
Wind	0.00	6.68	0.00	0.00	6.68
Totals	*1.45*	*30.27*	*1.67*	*25.02*	*58.41*

Table A.2. Gross primary fuels used to produce 1 kg PLA6 expressed as mass

Fuel type	Input (mg)
Crude oil	115,986
Gas/condensate	418,166
Coal	18,721
Metallurgical coal	132
Lignite	863
Peat	1
Wood	1

Table A.3. Gross water consumption required for the production of 1 kg PLA6

Source	Use for processing (mg)	Use for cooling (mg)	Totals (mg)
Public supply	31,603,108	12,153,903	43,757,011
River canal	1,788	1,072,007	1,073,795
Sea	1,034	11,376	12,409
Well	357,459	0	357,459
Unspecified	20,548,104	3,272,351	23,820,455
Totals	*52,511,493*	*16,509,636*	*69,021,129*

Sidebar A. The eco-profile of PLA6

Table A.4. Gross raw materials required to produce 1 kg PLA6

Raw material	Input (mg)
Barytes	560
Bauxite	6
Sodium chloride (NaCl)	114,426
Chalk ($CaCO_3$)	753,644
Clay	21,267
Fe	328
Pb	2
Limestone ($CaCO_3$)	35,252
Sand (SiO_2)	10,043
Phosphate as P_2O_5	6,501
S (elemental)	12,847
Dolomite	4
O_2	174
N_2	9,209
Air	886,350
Bentonite	39
Gravel	1
Olivine	3
Potassium chloride (KCl)	14,562
S (bonded)	254,260
Iron/steel scrap	67
Land use (x E-06 m^2)	1,699,680

Table A.5. Gross solid waste associated with the production of 1 kg PLA6

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Plastics	0	0	0	1,000	1,000
Unspecified refuse	1,005	0	0	0	1,005
Mineral waste	2	0	248	18,174	18,425
Slags & ash	459	334	96	24	913
Mixed industrial	795	0	26	1,391	2,212
Regulated chemicals	1,228	0	3,064	74	4,365
Unregulated chemicals	930	0	0	163	1,094
Construction waste	0	0	0	2	2
Inert chemical	0	0	0	1	1
Waste to recycling	0	0	0	1	1
Waste returned to mine	3,248	0	8	5	3,262
Tailings	0	0	9,548	179	9,727

Sidebar A. The eco-profile of PLA6

Table A.6. Gross air emissions associated with the production of 1 kg PLA6

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	From biomass (mg)	Totals (mg)
Dust (PM10)	570.6636	132.2103	37.8276	34.0286	0.0000	774.7301
CO	1,443.1528	1,284.0298	755.8766	2,295.0933	0.0000	5,778.1526
CO_2	55,532.9356	1,198,906.6562	111,891.3912	417,168.7731	-1,940,026.7197	-156,526.9636
SOx as SO_2	460.1360	1,637.3677	209.2154	158.3076	0.0000	2,465.0266
H_2S	0.0001	0.0590	0.1659	0.8713	0.0000	1.0963
Mercaptan	0.0000	0.0004	0.0000	0.0000	0.0000	0.0004
NOx as NO_2	160.6012	2,128.2407	1,609.1737	3,829.4798	0.0000	7,727.4954
NH_3	0.0000	0.0000	0.0007	4.9188	0.0000	4.9195
Cl_2	0.0000	0.0000	0.0001	0.1573	0.0000	0.1574
HCl	6.5007	2.8080	0.1494	0.0982	0.0000	9.5562
F_2	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
HF	0.2465	0.1353	0.0323	0.0000	0.0000	0.4142
Hydrocarbons not specified elsewhere	778.9060	322.5328	145.5795	14.8451	0.0000	1,261.8634
Aldehyde (-CHO)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Organics	0.0000	0.0000	0.0007	75.0717	0.0000	75.0725
Pb^+ compounds as Pb	0.0000	0.5605	0.0003	0.0007	0.0000	0.5615
Hg^+ compounds as Hg	0.0000	0.0000	0.0000	0.0002	0.0000	0.0003
Metals not specified elsewhere	0.0336	0.7098	0.0004	0.0012	0.0000	0.7450
H_2SO_4	0.0000	0.0000	0.0000	0.0135	0.0000	0.0135
N_2O	0.0000	0.3468	0.0000	364.9891	0.0000	365.3359
H_2	0.9599	0.0045	0.0044	141.7665	0.0000	142.7353
Dichloroethane (DCE) $C_2H_4Cl_2$	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001
Vinyl chloride monomer (VCM)	0.0000	0.0000	0.0022	0.0000	0.0000	0.0023
Organo-chlorine not specified elsewhere	0.0000	0.0000	0.0000	10.0037	0.0000	10.0037
HCN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	13,265.3942	487.3081	57.3004	38.2999	0.0000	13,848.3026
Aromatic HC not specified elsewhere	0.0045	0.0000	0.5938	0.1456	0.0000	0.7439
Polycyclic hydrocarbons (PAH)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NMVOC	0.0031	45.4368	259.9600	12.1822	0.0000	317.5822
CS_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methylene chloride (CH_2Cl_2)	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002
Cu^+ compounds as Cu	0.0000	0.0000	0.0000	0.0004	0.0000	0.0004
As^+ compounds as As	0.0000	0.0000	0.0000	0.0009	0.0000	0.0009
Cd^+ compounds as Cd	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002
Zn^+ compounds as Zn	0.0000	0.0000	0.0005	0.0015	0.0000	0.0020
Cr^+ compounds as Cr	0.0000	0.1463	0.0000	0.0003	0.0000	0.1466
Se^+ compounds as Se	0.0000	0.0000	0.0000	0.0005	0.0000	0.0005
Ni^+ compounds as Ni	0.0000	0.0000	0.0000	0.0033	0.0000	0.0033
Sb^+ compounds as Sb	0.0000	0.0000	0.0000	0.0002	0.0000	0.0003

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Sidebar A. The eco-profile of PLA6

Table A.6. Gross air emissions associated with the production of 1 kg PLA6 CONTINUED FROM PAGE 69

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	From biomass (mg)	Totals (mg)
Fe^+ compounds as Fe	0.0000	0.0000	0.0000	0.0023	0.0000	0.0023
Ethylene (C_2H_4)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Co^+ compounds as Co	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002
V^+ compounds as V	0.0000	0.0000	0.0000	0.0121	0.0000	0.0121
Al^+ compounds as Al	0.0000	0.0000	0.0000	-4.1388	0.0000	-4.1388
B^+ compounds as B	0.0000	0.0000	0.0000	0.0051	0.0000	0.0051
Manganese	0.0000	0.0000	0.0000	0.0006	0.0000	0.0006
Molybdenum	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Corn dust	0.0000	0.0000	0.0000	0.0000	75.1259	75.1259
Tin	0.0000	0.0000	0.0000	0.0005	0.0000	0.0005
Titanium	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Barium	0.0000	0.0000	0.0000	0.3515	0.0000	0.3515
Berylium	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bromine	0.0000	0.0000	0.0000	0.0042	0.0000	0.0042
Cyanide (unspecified)	0.0000	0.0000	0.0000	0.0009	0.0000	0.0009
Fluoride (unspecified)	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002
Helium	0.0000	0.0000	0.0000	0.3818	0.0000	0.3818
Strontium	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Volatile organic compounds (VOC)	0.0000	0.0000	0.0000	0.2449	0.0000	0.2449
Dust (PM 2.5)	0.0000	14.9290	0.0000	0.0000	0.0000	14.9290
Dust (unspecified)	0.0000	0.7216	64.5929	0.0000	0.0000	65.3145
Lactic acid	0.0000	0.0000	0.0000	0.8764	0.0000	0.8764
Particles (< 2.5 um)	0.0000	0.0000	0.0000	-20.9761	0.0000	-20.9761
Particles (>10 um)	0.0000	0.0000	0.0000	-255.6426	0.0000	-255.6426
Particles (<10 and > 2.5 um)	0.0000	0.0000	0.0000	-228.8741	0.0000	-228.8741

Table A.7. Gross emissions to water arising from the production of 1 kg PLA6

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
COD	1.1852	0.9615	21.5050	5881.2229	5904.8747
BOD	0.2467	0.0000	2.6595	1073.7634	1076.6697
Pb^+ compounds as Pb	0.0000	0.0000	0.0002	0.0001	0.0004
Fe^+ compounds as Fe	0.0001	0.0000	0.0136	12.8266	12.8403
Na^+ compounds as Na	0.1656	0.0000	0.1375	730.0261	730.3292
acid as H^+	0.5436	0.0000	0.0062	0.0189	0.5688
NO_3^-	0.0247	0.0000	0.0001	1206.9665	1206.9912
Hg^+ compounds as Hg	0.0000	0.0000	0.0000	0.0000	0.0000

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Sidebar A. The eco-profile of PLA6

Table A.7. Gross emissions to water arising from the production of 1 kg PLA6 Continued from page 70

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Metals not specified elsewhere	0.1342	0.0000	0.0051	0.0342	0.1736
Ammonium compounds as NH_4^+	0.6466	0.0000	0.0142	0.2212	0.8820
Cl^-	0.4125	0.0000	409.7747	1217.9034	1628.0905
CN^-	0.0000	0.0000	0.0005	0.0000	0.0005
F^-	0.0000	0.0000	3.8352	0.0487	3.8839
S^+ sulphides as S	0.0000	0.0000	0.0000	0.0000	0.0000
Dissolved organics (non-hydrocarbon)	0.4109	0.0000	0.0006	0.0772	0.4888
Suspended solids	4.5644	0.0000	24.9487	3064.7627	3094.2758
Detergent/oil	0.0001	0.0000	0.0148	0.0441	0.0590
Hydrocarbons not specified elsewhere	0.0548	0.0092	0.0120	1.4483	1.5243
Organo-chlorine not specified elsewhere	0.0000	0.0000	0.0000	0.0020	0.0020
Dissolved chlorine	0.0000	0.0000	0.0000	0.0018	0.0018
Phenols	0.0018	0.0000	0.0000	0.0060	0.0078
Dissolved solids not specified elsewhere	0.0041	0.0000	0.0613	4.0805	4.1459
P^+ compounds as P	0.0082	0.0001	0.0000	11.9749	11.9831
Other nitrogen as N	0.1206	0.0029	0.0051	84.3420	84.4707
Other organics not specified elsewhere	0.0000	0.0000	0.0006	0.3098	0.3104
SO_4^-	0.0003	0.0000	0.0467	138.5796	138.6267
Dichloroethane (DCE)	0.0000	0.0000	0.0000	0.0000	0.0000
Vinyl chloride monomer (VCM)	0.0000	0.0000	0.0000	0.0000	0.0000
K^+ compounds as K	0.0000	0.0000	0.0003	1.2141	1.2144
Ca^+ compounds as Ca	0.0000	0.0000	0.0009	127.3080	127.3089
Mg^+ compounds as Mg	0.0000	0.0000	0.0001	1.0652	1.0653
Cr^+ compounds as Cr	0.0000	0.0000	0.0000	0.0137	0.0137
ClO_3^-	0.0000	0.0000	0.0006	0.0630	0.0636
BrO_3^-	0.0000	0.0000	0.0000	0.0003	0.0003
TOC	0.0000	0.0000	9.5886	1558.8277	1568.4164
AOX	0.0000	0.0000	0.0002	0.0000	0.0002
Al^+ compounds as Al	0.0000	0.0000	0.0005	0.0844	0.0849
Zn^+ compounds as Zn	0.0000	0.0000	0.0001	0.0021	0.0021
Cu^+ compounds as Cu	0.0000	0.0000	0.0000	0.0010	0.0010
Ni^+ compounds as Ni	0.0000	0.0000	0.0000	0.0016	0.0016
CO_3^-	0.0000	0.0000	0.0190	0.2422	0.2613
As^+ compounds as As	0.0000	0.0000	0.0000	0.0006	0.0006
Cd^+ compounds as Cd	0.0000	0.0000	0.0000	0.0002	0.0002
Mn^+c ompounds as Mn	0.0000	0.0000	0.0000	0.0280	0.0280
Organo-tin as Sn	0.0000	0.0000	0.0000	0.0000	0.0000
Ag^+ compounds as Ag	0.0000	0.0000	0.0000	0.0003	0.0003
SO_3^-	0.0000	0.0000	0.0000	0.0000	0.0000
Ba^+ compounds as Ba	0.0000	0.0000	0.0000	0.0078	0.0078
Sr^+ compounds as Sr	0.0000	0.0000	0.0000	0.0282	0.0282
V^+ compounds as V	0.0000	0.0000	0.0000	0.0000	0.0000

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fertilizers) is 0.46 MJ/kg PLA. In the second bar (PLA6 Scope 2 electricity), RECs are purchased for the total quantity of electricity used in the Scope 1 processes, and so the environmental burden of this electricity (based on average electricity production in the MAPP area) is offset 1:1 with the environmental burden of electricity produced via wind power. The environmental burden of wind power production is based on a study by Vestas[9]. The energy content of the delivered fuel (natural gas, oil, electricity) at the operator is still 30.3 MJ/kg PLA, because the energy requirements of the involved processes remain the same, independent of whether the electricity is produced from wind or fossil fuels. However, a part of the delivered fuels now consists of wind energy (5.93MJ/kg PLA). The energy required to produce and deliver these fuels (the 30.3 MJ) dropped from 18.3 to 3.5 MJ/kg PLA. This drop in fuel production energy is the result of replacing fossil-based electricity with wind-based electricity and reflects the differences in efficiency between fossil-based and wind-based electricity production. Producing each MJ of fossil-based electricity delivered at the operator requires about 3.5 MJ of fossil fuel. For wind energy, the required fossil fuel is close to zero[9]. The GHG dropped from 2.02 to 0.47 kg CO_2 eq./kg PLA.

In the rightmost bar of *Figure 5* (PLA6 Scope 2+3 electricity), RECs are purchased for the total quantity of electricity used in the Cargill/NatureWorks (Scope 2) as well as the non-Cargill/NatureWorks-owned processes (part of Scope 3). The same procedure was used as for the Scope 2 emissions. The PLA production system uses 6.68 MJ electricity per kg PLA, of which 5.93 MJ is used in Scope 2 and 0.75 MJ in Scope 3 processes. This 0.75 MJ electricity is used in the production systems of dozens of products used somewhere in the PLA production system, including process and potable water, nitrogen, calcium hydroxide, carbon black, hydrochloric acid, sodium hydroxide, fertilizers, herbicides, and insecticides. The energy content of the delivered fuel (natural gas, oil, electricity) at the operator is still 30.3 MJ, because the energy requirements of the involved processes remain the same, independent of whether the electricity is produced from wind or fossil fuels. The part of the delivered fuels

Sidebar A. The eco-profile of PLA6

Table A.7. Gross emissions to water arising from the production of 1 kg PLA6 Continued from page 71

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Ca^{2+}	0.0000	0.0000	0.0000	247.7508	247.7508
PO_4^{3-}	0.0000	0.0000	0.0000	0.2434	0.2434
Chromium^{3+}	0.0000	0.0000	0.0000	0.0077	0.0077
Chromium^{4+}	0.0000	0.0000	0.0000	0.0005	0.0005
Heavy metals unspecified	0.0000	0.0000	0.0000	0.0003	0.0003
Molybdenum	0.0000	0.0000	0.0000	0.0001	0.0001
Selenium	0.0000	0.0000	0.0000	0.0000	0.0000
Titanium	0.0000	0.0000	0.0000	0.0000	0.0000
Chlorine dissolved	0.0000	0.0000	0.0000	0.0050	0.0050
Fluorine	0.0000	0.0000	0.0011	0.0001	0.0012
Neutral salts	0.0000	0.0000	0.0000	0.0255	0.0255
Halogenated organics	0.0000	0.0000	0.0000	0.0776	0.0776

Table A.8. Co-products arising from the production of 1 kg PLA6

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Gypsum monocell (temporary)	0	0	0	1,013,049	1,013,049
Landfilled waste (temporary)	0	0	0	204,624	204,624

coming from wind energy increased from 5.93 to 6.68 MJ/kg PLA. The energy required to produce and deliver these fuels (the 30.3 MJ/kg PLA) dropped from 18.3 to 1.66 MJ/kg PLA. The GHG emissions dropped from 2.02 to 0.27 kg CO_2 eq./kg PLA.

The gross or cumulative energy consumption for the three PLA polymer production systems is given in *Figure 6*. By replacing fossil-based electricity with wind energy in the PLA6 production system, the use of non-renewable fuels is reduced by 46%. The use of renewable fuels increased from 0.7 MJ/kg in the PLA5 case to 6.7 MJ/kg in the PLA6 case. With the introduction of new process technology, combined with green power in the PLA/NG production system, the non-renewable fuels are further reduced to 16.3 MJ/kg PLA—a reduction of 67% compared with the PLA5 case. The use of renewable fuels (mainly wind) declines slightly to 5.5 MJ/kg in the PLA/NG case. Also, the gross or total energy use (renewable and non-renewable) is reduced from 75.4 to 58.4 MJ/kg PLA in the PLA6 case, down to 45.9 MJ/kg PLA in the PLA/NG case.

Figure 7 (*p. 74*) gives the net cradle-to-polymer-factory-gate water use and emissions for GHG, NOx, SOx, hydrocarbons, and carbon monoxide for the three PLA production systems.

4.3. THE ECO-PROFILE FOR THE NEAR-FUTURE PLA PRODUCTION SYSTEM (PLA/NG)

This case represents the future or next-generation cradle-to-pellet PLA production system. This production system is expected to be introduced in a few years, reducing the environmental footprint of PLA via the implementation of new process technology. To protect proprietary interests, further details cannot be given at this time. As a result of the new technology, the dextrose, lime, sulfuric acid, steam, and natural gas intake will be reduced, and the production of co-products having little value eliminated. Green power is expected to be used to supply electricity in the Cargill/NatureWorks controlled production processes. In the PLA/NG production system, no RECs are purchased to meet the electricity requirements in non-Cargill/NatureWorks facilities (Scope 3 processes in Section 3.5), since the cradle-to-factory-gate GHG balance is already negative.

The eco-profile data for the PLA/NG production system is given in *Sidebar B* (*p. 75*). The data represents a produc-

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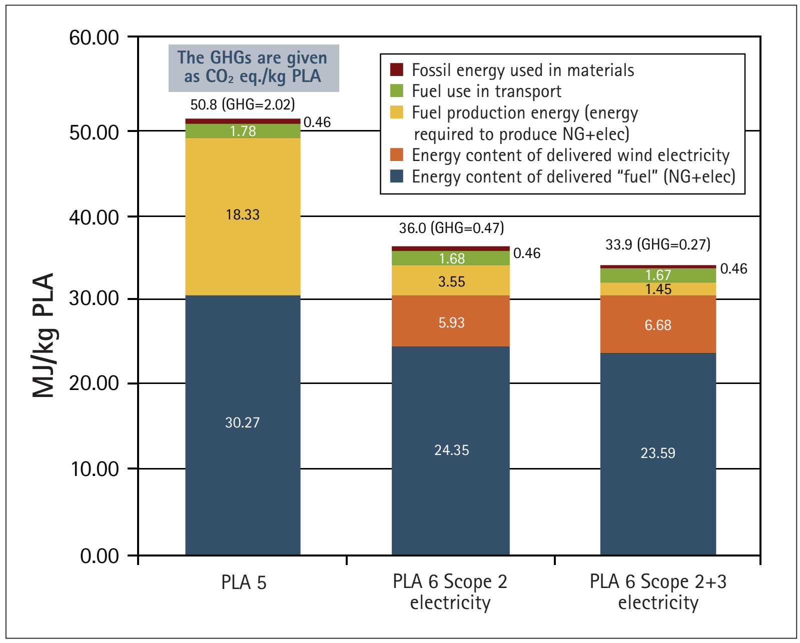

Figure 5. Results of the three- step procedure: the gross primary energy used to produce 1 kg PLA

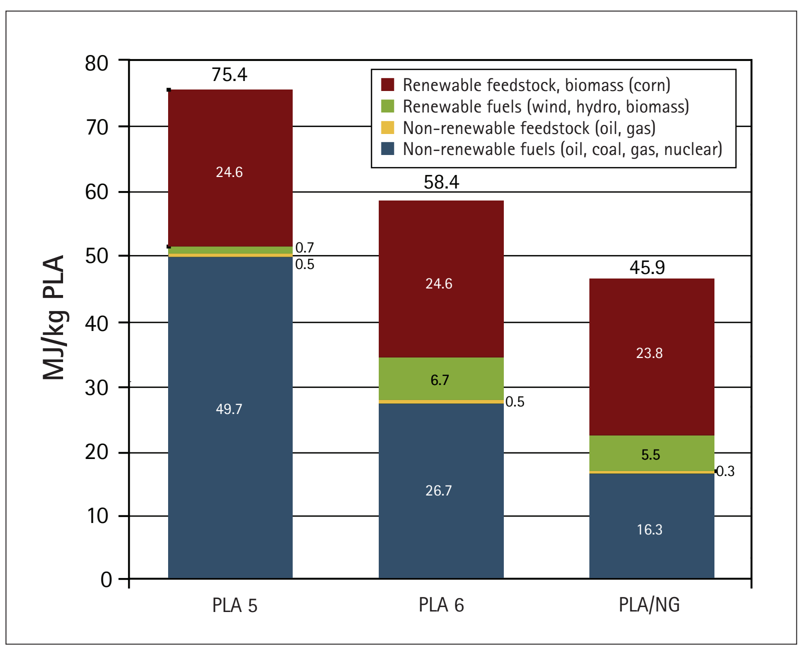

Figure 6. Cradle-to-polymer-factory-gate gross energy use for the various PLA production systems

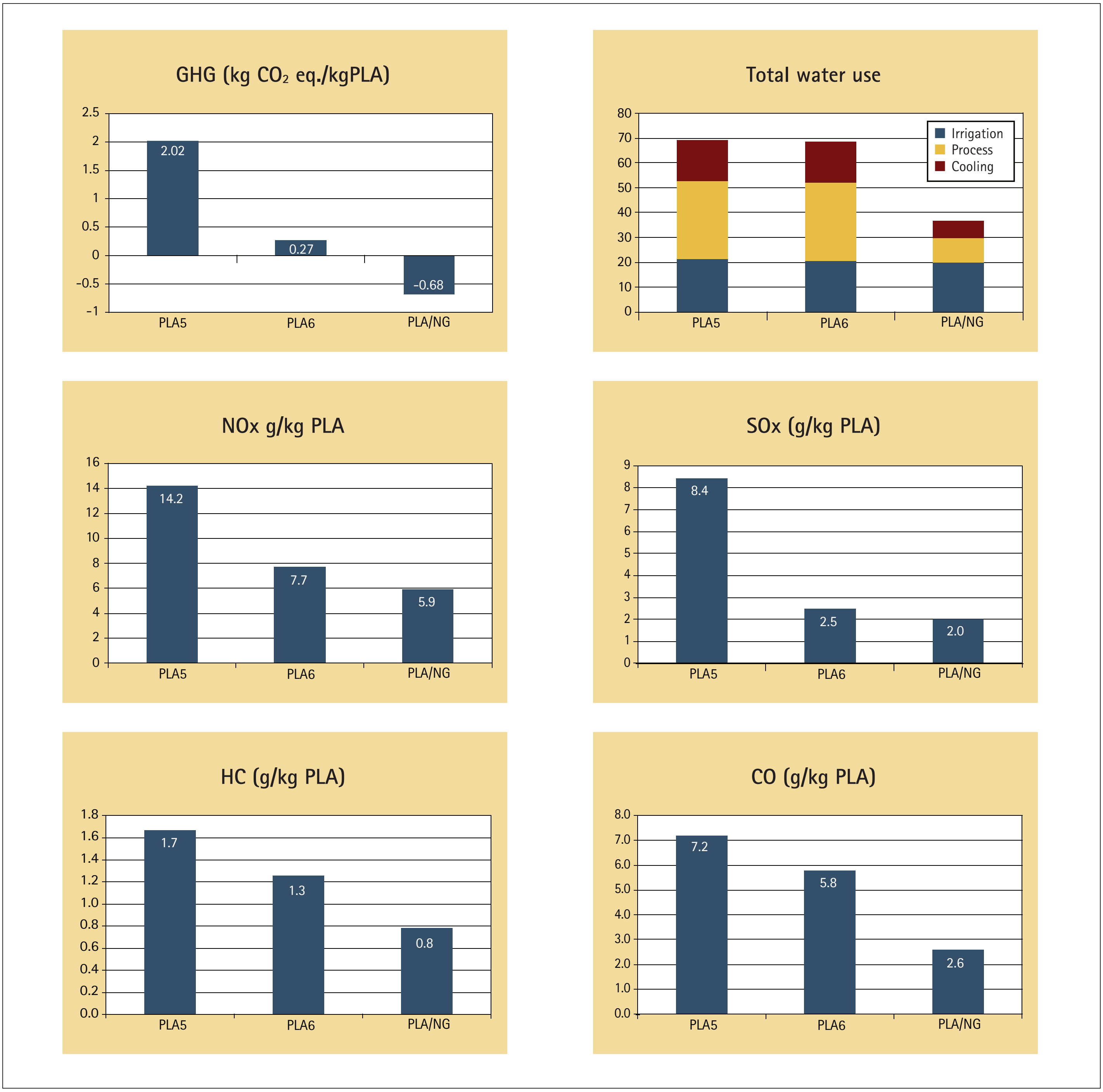

Figure 7. Cradle-to-polymer-factory-gate water use and emissions for the various PLA cases

Sidebar B. The eco-profile of PLA/NG

Table B.1. Gross primary fuels and feedstock required to produce 1 kg of PLA/NG

Fuel type	Fuel production & delivery energy (MJ)	Energy content of delivered fuel (MJ)	Fuel use in transport (MJ)	Feedstock energy (MJ)	Total energy (MJ)
Coal	0.55	0.34	0.01	0.00	0.89
Oil	0.10	1.91	0.39	0.20	2.59
Gas	1.02	12.00	0.01	0.04	13.07
Hydro	0.03	0.01	0.00	0.00	0.04
Nuclear	0.31	0.12	0.00	0.00	0.44
Lignite	0.01	0.00	0.00	0.00	0.01
Wood	0.00	0.00	0.00	0.00	0.00
Sulfur	0.00	0.01	0.00	0.06	0.07
Biomass (solid)	0.00	0.00	0.00	23.84	23.84
Hydrogen	0.00	0.03	0.00	0.00	0.03
Recovered energy	0.00	-0.53	0.00	0.00	-0.53
Unspecified	0.00	0.00	0.00	0.00	0.00
Peat	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00
Wave/tidal	0.00	0.00	0.00	0.00	0.00
Biomass (liquid/gas)	0.00	0.00	0.00	0.00	0.00
Industrial waste	0.00	0.00	0.00	0.00	0.00
Municipal waste	0.00	0.00	0.00	0.00	0.00
Wind	0.00	5.47	0.00	0.00	5.47
Totals	2.02	19.36	0.41	24.14	45.92

Table B.2. Gross primary fuels used to produce 1 kg PLA/NG expressed as mass

Fuel type	Input (mg)
Crude oil	57,065
Gas/condensate	247,986
Coal	30,723
Metallurgical coal	121
Lignite	572
Peat	1
Wood	1

Table B.3. Gross water consumption required for the production of 1 kg PLA/NG

Source	Use for processing (mg)	Use for cooling (mg)	Totals (mg)
Public supply	9,620,653	5,262,158	14,882,812
River canal	719	297,537	298,256
Sea	421	5,311	5,733
Well	48,225	0	48,226
Unspecified	19,926,166	1,472,638	21,398,804
Totals	29,596,184	7,037,645	36,633,829

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Table B.4. Gross raw materials required to produce 1 kg PLA/NG

Raw material	Input (mg)
Barytes	72
Bauxite	3
Sodium chloride (NaCl)	38,970
Chalk (CaCO)	101,673
Clay	109
Fe	301
Pb	2
Limestone ($CaCO_3$)	33,530
Sand (SiO_2)	10,964
Phosphate as P_2O_5	7,309
S (elemental)	7,622
Dolomite	4
O_2	73
N_2	8,513
Air	259,078
Bentonite	5
Gravel	1
Olivine	3
Potassium chloride (KCl)	14,135
S (bonded)	32,706
Iron/steel scrap	55
Land use (x E-06 m^2)	1,649,913

Table B.5. Gross solid waste associated with the production of 1 kg PLA/NG

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Plastics	0	0	0	1,000	1,000
Unspecified refuse	528	0	0	0	528
Mineral waste	5	0	230	17,328	17,564
Slags & ash	2,114	369	89	10	2,583
Mixed industrial	441	0	11	1,335	1,788
Regulated chemicals	645	0	394	12	1,051
Unregulated chemicals	489	0	0	158	647
Construction waste	0	0	0	1	1
Inert chemical	0	0	0	1	1
Waste to recycling	0	0	0	1	1
Waste returned to mine	5,823	0	8	2	5,833
Tailings	0	0	1,234	23	1,257

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Table B.6. Gross air emissions associated with the production of 1 kg PLA/NG

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	From biomass (mg)	Totals (mg)
Dust (PM10)	575.7874	91.2292	14.1765	22.6042	0.0000	703.7973
CO	913.2112	978.5123	205.7401	497.3944	0.0000	2,594.8579
CO_2	131,365.8647	690,278.6179	27,097.8359	116,389.6974	-1,934,625.1027	-969,493.0868
SOx as SO_2	500.0888	1,281.1966	65.8713	152.5142	0.0000	1,999.6710
H_2S	0.0002	0.0483	0.0297	0.1122	0.0000	0.1904
Mercaptan	0.0000	0.0004	0.0000	0.0000	0.0000	0.0004
NOx as NO_2	334.3863	1,539.0099	356.8825	3,703.0829	0.0000	5,933.3617
NH_3	0.0000	0.0000	0.0006	3.9285	0.0000	3.9291
Cl_2	0.0000	0.0000	0.0001	0.1136	0.0000	0.1136
HCl	14.4128	2.8297	0.0416	0.0393	0.0000	17.3235
F_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HF	0.5373	0.1022	0.0048	0.0000	0.0000	0.6443
Hydrocarbons not specified elsewhere	417.2711	298.2383	56.8371	11.7704	0.0000	784.1169
Aldehyde (-CHO)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Organics	0.0000	0.0000	0.0007	6.5019	0.0000	6.5026
Pb^+ compounds as Pb	0.0000	0.4587	0.0003	0.0001	0.0000	0.4591
Hg^+ compounds as Hg	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Metals not specified elsewhere	0.0225	0.6979	0.0003	0.0005	0.0000	0.7212
H_2SO_4	0.0000	0.0000	0.0000	0.0054	0.0000	0.0054
N_2O	0.0000	0.2838	0.0000	354.0147	0.0000	354.2985
H_2	0.5709	0.0039	0.0041	46.1115	0.0000	46.6903
Dichloroethane (DCE; $C_2H_4Cl_2$)	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001
Vinyl chloride monomer (VCM)	0.0000	0.0000	0.0020	0.0000	0.0000	0.0021
Organo-chlorine not specified elsewhere	0.0000	0.0000	0.0000	3.9976	0.0000	3.9976
HCN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	7,710.6549	468.4366	7.4286	19.0297	0.0000	8,205.5497
Aromatic HC not specified elsewhere	0.0120	0.0000	0.5494	0.0582	0.0000	0.6196
Polycyclic hydrocarbons (PAH)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nonmethane volatile organic compounds (NMVOC)	0.0014	23.6388	33.4399	9.1886	0.0000	66.2686
CS_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methylene chloride (CH_2Cl_2)	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002
Cu^+ compounds as Cu	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
As^+ compounds as As	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Cd^+ compounds as Cd	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Zn^+ compounds as Zn	0.0000	0.0000	0.0004	0.0002	0.0000	0.0006
Cr^+ compounds as Cr	0.0000	0.1197	0.0000	0.0000	0.0000	0.1198
Se^+ compounds as Se	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Ni^+ compounds as Ni	0.0000	0.0000	0.0000	0.0004	0.0000	0.0004

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Table B.6. Gross air emissions associated with the production of 1 kg PLA/NG Continued from page 77

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	From biomass (mg)	Totals (mg)
Sb^+ compounds as Sb	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fe^+ compounds as Fe	0.0000	0.0000	0.0000	0.0003	0.0000	0.0003
Ethylene (C_2H_4)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Co^+ compounds as Co	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
V^+ compounds as V	0.0000	0.0000	0.0000	0.0016	0.0000	0.0016
Al^+ compounds as Al	0.0000	0.0000	0.0000	-1.8682	0.0000	-1.8682
B^+ compounds as B	0.0000	0.0000	0.0000	0.0007	0.0000	0.0007
Manganese	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Molybdenum	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Corn dust	0.0000	0.0000	0.0000	0.0000	72.9262	72.9262
Tin	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Titanium	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Barium	0.0000	0.0000	0.0000	0.0452	0.0000	0.0452
Berylium	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bromine	0.0000	0.0000	0.0000	0.0005	0.0000	0.0005
Cyanide (unspecified)	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Fluoride (unspecified)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Helium	0.0000	0.0000	0.0000	0.0491	0.0000	0.0491
Strontium	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Volatile organic compounds (VOC)	0.0000	0.0000	0.0000	0.0315	0.0000	0.0315
Dust (PM 2.5)	0.0000	1.9204	0.0000	0.0000	0.0000	1.9204
Dust (unspecified)	0.0000	0.0928	8.3088	0.0000	0.0000	8.4016
Lactic acid	0.0000	0.0000	0.0000	0.8764	0.0000	0.8764
Particles (< 2.5 um)	0.0000	0.0000	0.0000	-11.5509	0.0000	-11.5509
Particles (>10 um)	0.0000	0.0000	0.0000	-121.2327	0.0000	-121.2327
Particles (<10 and > 2.5 um)	0.0000	0.0000	0.0000	-108.9472	0.0000	-108.9472
Acetic acid	0.0000	0.0000	0.0000	1.1344	0.0000	1.1344

Table B.7. Gross emissions to water arising from the production of 1 kg PLA/N

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
COD	0.8079	0.7869	2.9448	4,859.2916	4,863.8312
BOD	0.1290	0.0000	0.3424	891.0130	891.4844
Pb^+ compounds as Pb	0.0000	0.0000	0.0002	0.0000	0.0002
Fe^+ compounds as Fe	0.0003	0.0000	0.0126	4.9563	4.9691
Na^+ compounds as Na	0.0888	0.0000	0.1273	256.9765	257.1925
Acid as H^+	0.5624	0.0000	0.0058	0.0153	0.5835

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Sidebar B. The eco-profile of PLA/NG

Table B.7. Gross emissions to water arising from the production of 1 kg PLA/N CONTINUED FROM PAGE 78

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
NO^{3-}	0.0129	0.0000	0.0001	1,171.6201	1,171.6331
Hg^+ compounds as Hg	0.0000	0.0000	0.0000	0.0000	0.0000
Metals not specified elsewhere	0.1381	0.0000	0.0047	0.0160	0.1588
Ammonium compounds as NH_4^+	0.5849	0.0000	0.0132	0.0455	0.6435
Cl^-	0.2190	0.0000	52.8813	486.4394	539.5396
CN^-	0.0000	0.0000	0.0001	0.0000	0.0001
F^-	0.0000	0.0000	0.4945	0.0071	0.5016
S^+ sulphides as S	0.0000	0.0000	0.0000	0.0000	0.0000
Dissolved organics (non-hydrocarbon)	0.2148	0.0000	0.0006	0.0566	0.2719
Suspended solids	7.8671	0.0000	23.1499	2,744.1076	2,775.1245
Detergent/oil	0.0003	0.0000	0.0137	0.0176	0.0316
Hydrocarbons not specified elsewhere	0.0233	0.0078	0.0111	0.1874	0.2296
Organo-chlorine not specified elsewhere	0.0000	0.0000	0.0000	0.0017	0.0017
Dissolved chlorine	0.0000	0.0000	0.0000	0.0017	0.0017
Phenols	0.0009	0.0000	0.0000	0.0025	0.0034
Dissolved solids not specified elsewhere	0.0038	0.0000	0.0534	3.1025	3.1598
P^+ compounds as P	0.0043	0.0001	0.0000	11.5800	11.5844
Other nitrogen as N	0.1248	0.0024	0.0048	235.7253	235.8573
Other organics not specified elsewhere	0.0000	0.0000	0.0006	0.1238	0.1244
SO_4^-	0.0009	0.0000	0.0432	117.6874	117.7316
Dichloroethane (DCE)	0.0000	0.0000	0.0000	0.0000	0.0000
Vinyl chloride monomer (VCM)	0.0000	0.0000	0.0000	0.0000	0.0000
K^+ compounds as K	0.0000	0.0000	0.0003	0.1697	0.1700
Ca^+ compounds as Ca	0.0000	0.0000	0.0008	50.3630	50.3638
Mg^+ compounds as Mg	0.0000	0.0000	0.0001	0.3833	0.3834
Cr^+ compounds as Cr	0.0000	0.0000	0.0000	0.0018	0.0018
ClO^+	0.0000	0.0000	0.0005	0.0567	0.0572
BrO^{3-}	0.0000	0.0000	0.0000	0.0002	0.0002
TOC	0.0000	0.0000	1.2339	1,377.6053	1,378.8392
AOx	0.0000	0.0000	0.0000	0.0000	0.0000
Al^+ compounds as Al	0.0000	0.0000	0.0004	0.0114	0.0118
Zn^+ compounds as Zn	0.0000	0.0000	0.0001	0.0003	0.0004
Cu^+ compounds as Cu	0.0000	0.0000	0.0000	0.0003	0.0003
Ni^+ compounds as Ni	0.0000	0.0000	0.0000	0.0003	0.0003
CO^{3-}	0.0000	0.0000	0.0182	0.1103	0.1285
As^+ compounds as As	0.0000	0.0000	0.0000	0.0001	0.0001
Cd^+ compounds as Cd	0.0000	0.0000	0.0000	0.0000	0.0000
Mn^+ compounds as Mn	0.0000	0.0000	0.0000	0.0036	0.0036
Organo-tin as Sn	0.0000	0.0000	0.0000	0.0000	0.0000
Ag^+ compounds as Ag	0.0000	0.0000	0.0000	0.0000	0.0000
SO^{3-}	0.0000	0.0000	0.0000	0.0000	0.0000
Ba^+ compounds as Ba	0.0000	0.0000	0.0000	0.0010	0.0010

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Sidebar B. The eco-profile of PLA/NG

Table B.7. Gross emissions to water arising from the production of 1 kg PLA/N CONTINUED FROM PAGE 79

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Sr^{+} compounds as Sr	0.0000	0.0000	0.0000	0.0036	0.0036
V^{+} compounds as V	0.0000	0.0000	0.0000	0.0000	0.0000
Ca^{2+}	0.0000	0.0000	0.0000	240.4711	240.4711
PO_4^{3-}	0.0000	0.0000	0.0000	0.0313	0.0313
Chromium^{3+}	0.0000	0.0000	0.0000	0.0010	0.0010
Chromium^{4+}	0.0000	0.0000	0.0000	0.0001	0.0001
Heavy metals, unspecified	0.0000	0.0000	0.0000	0.0000	0.0000
Molybdenum	0.0000	0.0000	0.0000	0.0000	0.0000
Selenium	0.0000	0.0000	0.0000	0.0000	0.0000
Titanium	0.0000	0.0000	0.0000	0.0000	0.0000
Chlorine dissolved	0.0000	0.0000	0.0000	0.0006	0.0006
Fluorine	0.0000	0.0000	0.0001	0.0000	0.0002
Neutral salts	0.0000	0.0000	0.0000	0.0033	0.0033
Halogenated organics	0.0000	0.0000	0.0000	0.0100	0.0100

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tion of 140,000 t/year. *Table B.1* shows the gross primary fuels and feedstock requirements. The biomass entry in the Feedstock energy column (23.84 MJ) represents the corn intake. The energy content of corn is 16.3 MJ/kg corn. *Table B.2* shows the energy data expressed as the mass of fuel used. *Table B.3* shows the demand for water. The entry "Unspecified" in the "Use for processing column" mainly represents the irrigation water use during corn production. *Table B.4* shows the raw material requirements. The bottom entry gives "Land use"; the land use is 1.65 m^2/kg PLA. *Table B.5* shows the solid waste generated, and *Table B.6* shows the air emissions. Finally, *Table B.7* shows the emissions to water. The interpretation of these tables is described by Boustead[6].

5. Conclusion

PLA production in 2006 emitted 0.27 kg CO_2 eq./kg PLA and used 27.2 MJ/kg PLA of fossil energy, representing reductions of 85% and 50%, respectively, compared to the 2003 PLA eco-profile data. The reductions in GHG emission and fossil energy use are due in large part to the use of wind power for PLA production. In 2004[25], NatureWorks reported its plans to start using wind power-derived RECs to reduce the environmental impact of PLA production. Starting in January 2006, PLA production reached a level triggering NatureWorks' purchase of the certificates in an amount equivalent to the electricity used in the PLA production system. From the results it is clear that the utilization of wind energy has a very positive effect on the environmental footprint of the PLA production system. Further significant reductions can be achieved by the implementation of new process technology, again in combination with the use of renewable energy.

Wind-derived RECs are available to any company using electricity. NatureWorks actively sought out renewable energy solutions to combine with its renewable feedstock. Should others follow, it would be a big push for renewable energy generation leading to reduced fossil fuels use. As noted by Kathleen Hogan, director of the US EPA's climate protection partnership division, the purchasing of green power is a simple, effective way for corporations to reduce their GHG emissions and the risks associated with global climate change. These voluntary green power purchases are also helping to accelerate the development of new clean-generation facilities across the United States. There is some debate over whether RECs actually reduce GHG-emitting power generation. The argument is sometimes offered that the actual energy the companies use continues to be derived predominatly from carbon-emitting fossil fuels, since the green power supported by RECs is not actually being consumed by the company paying for the RECs. This is not a valid argument, since there is a corresponding amount of power from fossil fuel-derived generation being offset, independent of where the power is being generated[26]. RECs are a recognized means of offsetting the environmental burden of fossil fuel-based electricity and support the development of renewable energy.

PLA is a relatively new material. PP, PS, and PET are commodities produced in large-scale facilities that have been optimized over many years of commercialization. PLA certainly still is at a much earlier phase of market development and process optimization, and since most LCAs are an input for forward-looking decision-making processes the benefits of moving toward PLA/NG should also be considered.

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During the development process of the eco-profiles for NatureWorks PLA, Dr. Ian Boustead of Boustead Consulting and Prof. Dr. Bruce Dale of Michigan State University reviewed the intermediate and final reports. Both review reports may be downloaded from the NatureWorks LLC website[2]. The application of the GHG protocol (Section 3.5) and RECs (Section 3.6) were reviewed by World Resource Institute GHG Protocol team members[27]. Herewith we would like to acknowledge all their input.

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