

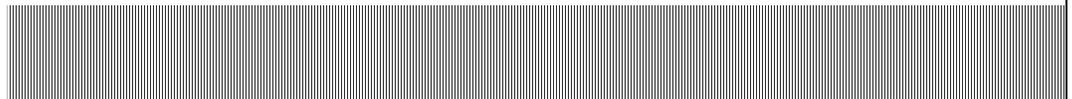


LEHIGH TECHNOLOGIES

Redefining the Science of Powder Technology

Greenhouse Gas Inventory and Product Life Cycle Analysis – Phase II

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5989-001

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Contents

1. Introduction	1-1
2. Background and Methodology	2-1
2.1. Background.....	2-1
2.2. Life Cycle Assessment.....	2-2
3. Product Life Cycle Assessment	3-1
3.1. PolyDyne™ Lifecycle GHG Emissions	3-1
3.2. Comments from SimaPro Compound List	3-3
3.3. Competitor Compounds' Lifecycle GHG Emissions and Energy Requirements	3-5
4. Conclusions/Recommendations	4-1

List of Tables

Table 3-1. Recycled Tire CO ₂ Inventory.....	3-2
Table 3-2. PolyDyne™ Equivalent Crude Oil	3-2
Table 3-3. Sima Pro Virgin Compound GHG LCA Emissions and PolyDyne™ CO ₂ Net Savings.....	3-5
Table 3-4 GHG LCA Emissions and Manufacturing Energy from Australia Study.....	3-6
Table 3-5 Energy and GHG per kg of Tire from Australia Study.....	3-6
Table 3-6 Energy and GHG per kg of Tire from Continental LCA.....	3-6
Table 3-7. Virgin Plastic/Rubber Gross Energy Requirements	3-7
Table 3-8. Gross Energy Requirement Comparison (BTU/lb product).....	3-8

List of Figures

Figure 2-1: Swiss Databases Using in SimaPro.....	2-2
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Appendices

A. Calculations



1. Introduction

The mission of Lehigh Technologies (Lehigh), manufacturers of the PolyDyne™ family of fine and ultra-fine rubber powders, is to “redefine the markets for rubber, industrial inputs and specialty chemicals by using proprietary technologies, innovative processes and re-claimed raw materials to produce products with superior price-to-performance characteristics and provide them to customers with world class quality, service and reliability.” Lehigh sells its product to various industries that substitute rubber powder made from old tires instead of virgin, petroleum-based rubber. These fine and ultra-fine recycled rubber powders can be found in latex and polymer-based paints, plastics, automobile accessories (tires, brakes, belts, etc.), shoes, floor tiles, asphalt, and roofing material.

In order to further understand the beneficial environmental impact of the PolyDyne™ process, Lehigh retained Malcolm Pirnie to investigate the greenhouse gas (GHG) inventory and product life cycle analysis of the compounds displaced by the use of the Lehigh recycled rubber powder. The objectives of this project include the following:

- Review literature articles and national databases to determine the energy requirements to produce virgin acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE), styrene butadiene rubber (SBR), ethylene propylene diene monomer (EPDM), and acrylonitrile butadiene rubber (NBR).
- Review literature articles and national databases to determine the GHGs emitted when producing virgin ABS, PVC, PP, PE, SBR, EPDM, and NBR. Particular attention will be paid to carbon dioxide (CO₂), as it is the largest GHG contributor.
- Review literature articles and national databases to determine the amount of crude oil needed to produce virgin ABS, PVC, PP, PE, SBR, EPDM, and NBR. If data do not exist, the equivalent amount of crude oil will be determined based on the gross energy requirements.
- Prepare a technical memorandum summarizing the findings and the GHG and energy benefits/disbenefits of using recycled PolyDyne™ rubber instead of ABS, PVC, PP, PE, SBR, EPDM, and NBR.

2. Background and Methodology

2.1. Background

Phase I of the GHG Inventory and Product Life Cycle Analysis determined Lehigh's CO₂ emissions based on the *GHG Protocol Corporate Accounting and Report Standard* (*GHG Protocol Corporate Standard*) published by the World Business Council for Sustainable Development. The *GHG Protocol Corporate Standard* covers the accounting and reporting of the six greenhouse gases covered by the Kyoto protocol – carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). Other methods for determining GHG inventories exist and are used throughout the world. When comparing inventories, it is important to consider the method by which the GHG inventories were calculated. Some inventories may only include direct emissions, while other inventories include all emissions associated with a particular product from the cradle to the grave.

When calculating a GHG inventory, the *GHG Protocol Corporate Standard* contains emissions factors for various energy sources. This document sets a standard emission factor for each energy source (diesel, electricity, oil, natural gas, etc.) to minimize the variability when comparing product emissions. This “standard emission factor,” however will vary depending on the agency that develops the protocol because of geographic variation or different methodologies. For this reason, comparing product inventory data developed from different protocols and geographic regions can be challenging. Furthermore, only aggregate emissions are reported at the corporate level; companies rarely report emissions for specific compounds because of privacy concerns. For this reason, a different life cycle assessment approach was used for Phase 2 of this project.

2.2. Life Cycle Assessment

By definition, a life cycle assessment (LCA) is a technique for assessing the environmental impacts associated with a product (or service), by:

- 1) Compiling an inventory of relevant inputs and outputs
- 2) Evaluating the potential environmental impacts associated with those inputs and outputs
- 3) Interpreting the results of the inventory and impact phases in relation to the objectives of the study.¹

Software is commercially available that allows a company or organization to conduct a life cycle assessment for a particular product. This software usually combines multiple inventory datasets which are normalized based on mass and/or revenue. The most widely-used LCA software in this category is SimaPro. The foundation of SimaPro is the Ecoinvent dataset which contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services. This dataset is the result of a large effort by Swiss institutes to update and integrate ETH-ESU 96, BUWAL250, and several other databases into a single central database (Figure 2-1). While SimaPro is largely based on European industrial processes, the software is used globally because no other databases of this magnitude exist in other countries.

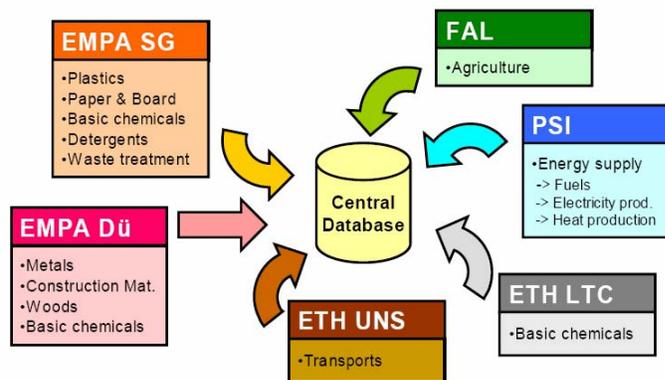


Figure 2-1: Swiss Databases Using in SimaPro²

SimaPro uses historical data to estimate the total impact a particular product has on the environment by identifying all the raw inputs from and outputs to the air, water, and/or ground. If data are not available for a particular process, a system process can be developed from multiple unit processes to estimate the LCA. For example, SBR can be

¹ ISO 14040.2 Draft: Life Cycle Assessment – Principles and Guidelines

² Ecoinvent Centre. [Online]. Available: <<http://www.ecoinvent.ch>>. [cited June 2007]

made by a single company that processes crude oil into SBR. If such a company does not exist, a system process can be designed by combining a styrene unit process with a butadiene unit process in the desired proportions. This system process can then be saved and made into a unit process for SBR. Because the dataset is a combination of other datasets, multiple entries for a similar product exist. In such cases, the process that most represents the desired product can be used or a range can be determined for the general product.

SimaPro's boundaries differ from the *GHG Protocol Corporate Standard*. To avoid double-counting emissions, the *GHG Protocol Corporate Standard* reports only direct emissions from the use of fuels. For example, one gallon of diesel fuel emits 22.33 lbs of CO₂ when burned³. It does not account for the energy and emissions associated with extraction, refining, and transportation.

SimaPro, on the other hand, will account for the complete life cycle of emissions which results in an additional 0.62 lbs CO₂ per gallon of diesel for a total of 22.92 lbs of CO₂ per gallon of diesel used. In order to compare ABS, PVC, PP, PE, SBR, EPDM, and NBR products to Lehigh's, a LCA was determined for the PolyDyne™ rubber using a similar methodology that included an estimate of CO₂ emissions from the grinding process performed before the scrap rubber arrives at the Lehigh production facility.

Tires are not produced specifically for the PolyDyne™ process, so only the energy inputs required to process a scrap tire and deliver the rubber powder to the end user are considered. Recycled PolyDyne™ rubber can be used as an alternative to virgin ABS, PVC, PP, PE, SBR, EPDM, and NBR. As such, the process CO₂ emissions and gross energy requirements (feedstock and process) determined from the LCA for virgin plastics and rubbers were compared to PolyDyne™ rubber. The savings associated with using virgin versus recycled plastic/rubber were calculated to determine the benefit to the environment.

In addition to determining the process CO₂ emissions and gross energy requirements for virgin plastics/rubbers and recycled PolyDyne™ rubber, the equivalent amount of crude oil needed to produce a pound of product was estimated based on the combined feedstock and process energy requirements. Actual quantities of crude oil needed for the process will vary because process energy and feedstocks can be obtained from multiple sources (coal, natural gas, crude oil).

³ California Climate Action Registry General Reporting Protocol Version 2.2, March 2007. Table C.3 page 89.

3. Product Life Cycle Assessment

3.1. PolyDyne™ Lifecycle GHG Emissions

The conditions and assumptions for the PolyDyne™ process are based on information provided by Lehigh. The calculations and comparisons that follow are meant for qualitative use only and may not be used for certification purposes by an outside agency such as CCAR, or CCX. If certification is desired, CO₂ emissions need to be based on actual historical data for at least one year of production. The historical data should include both building energy and the energy requirements for the production lines.

As indicated in Phase I, the Lehigh PolyDyne™ production facility contains four production lines that require 18,100,000 kWh/year of electricity and 149,000,000 lbs of liquid nitrogen. In addition, approximately 52,000 gallons/year of diesel fuel are used to transport raw materials and finished goods. These three items have been identified as the three largest GHG emitters (either direct or indirect) in the process, totaling greater than 95 percent of the total emissions. The CO₂ inventory in Phase I was estimated at 0.7 lbs CO₂/lb product. This estimate did not include the electricity or diesel fuel emissions associated with collecting used tires from landfills and shredding them into 1-inch cubes. In order to compare the PolyDyne™ process to the compounds of interest in this study, these emissions should be included in the overall life cycle assessment.

Table 3-1 summarizes the revised CO₂ emissions, which includes diesel fuel transportation emissions prior to shredding and tire shredding emissions (into 1-inch cubes). The table also includes a revised liquid nitrogen LCA emission factor that was determined through SimaPro⁴. These calculations represent a conservative estimate as some electric grids utilize power sources that have low greenhouse gas emissions (solar, wind, hydropower) in greater proportions than is assumed in SimaPro.

Based on Table 3-1, the life cycle assessment CO₂ emissions are 108,000,000 lb CO₂/year based on a production rate of 136,000,000 lb/year. The relative emissions are 0.79 lb CO₂/ lb product. Total primary energy requirements and equivalent crude oil volume (not including the energy contained in the scrap tire) needed were also calculated for the life cycle assessment, shown in Table 3-2. This includes the energy requirements associated with electricity and nitrogen production as well as diesel fuel production and use. The primary energy for the liquid nitrogen and diesel fuel unit processes are based on the sum of raw energy requirements calculated from SimaPro (2,800 BTU/lb and

⁴ Product Ecology Consultants. SimaPro 7: N2 ETH U Unit Process LCA. Product Ecology Consultants.

21,800 BTU/lb, respectively). Electricity primary energy in Table 3-2 are based on heat rates from the SERC (south) inputs/outputs⁵ and do not include de minimus emissions from fuel transport estimated to be less than 3 percent. The equivalent crude oil value (42.6 MJ/kg, 850 kg/m³)⁶ for the PolyDyne™ process is 0.04 gallons per pound of product.

**Table 3-1.
Recycled Tire CO₂ Inventory**

Input	Quantity/Year	CO ₂ Emission Factor	CO ₂ Emissions
Scope 1			0 lb
Scope 2			29,000,000 lb
Electricity	18,100,000 kWh	1.60 lb CO ₂ /kWh ⁷	29,000,000 lb
Scope 3			78,900,000 lb
Liquid Nitrogen (LN2)	149,000,000 lb	0.28 lb CO ₂ /lb	41,700,000 lb
Third Party Transportation	310,000 miles (52,000 gallons diesel)	22.95 lb CO ₂ /gallon ⁸	1,200,000 lb
Preliminary Tire Shredding			
Shredding	12,800,000 kWh	1.60 lb CO ₂ /kWh	20,400,000 lb
Transportation (diesel)	680,000 gallons diesel	22.95 lb CO ₂ /gallon	15,600,000 lb
Total			108,000,000 lb

**Table 3-2.
PolyDyne™ Equivalent Crude Oil**

Input	Quantity (per lb product)	Primary Energy	Primary Energy Required	Equivalent Crude Oil
Electricity	0.133 kWh	8,000 BTU/kWh	1,064 BTU/lb	0.0082 gal/lb
Liquid Nitrogen	1.1 lb LN2	2,800 BTU/lb LN2	3,080 BTU/lb	0.02 gal/lb
Third Party Transportation	0.00038 gal	21,800 BTU/lb	60 BTU/lb	0.0005 gal/lb
Preliminary Tire Shredding				
Shredding	0.093 kWh	8,000 BTU/kWh	750 BTU/lb ⁹	0.006
Transportation (diesel)	0.005 gal	21,800 BTU/lb	750 BTU/lb ⁹	0.006
Total				0.04 gal/lb

⁵ U. S. EPA eGRID2006 Version 2.1: Subregion Location(Operator)-based File (Year 2004 Data) [Online]. Available: <<http://www.epa.gov/cleanenergy/egrid/index.htm>>. [cited June 2007].

⁶ Product Ecology Consultants. SimaPro 7.

⁷ California Climate Action Registry General Reporting Protocol Version 2.2, March 2007. Table C.1 SRSO, page 86.

⁸ As calculated in section 2.2.

⁹ Sousa, J., G. Way, and D. Carlson. Table 2: BTU Utilization for TDF. *Cost Benefit Analysis and Energy Consumption of Scrap Tire Management Options*.

3.2. Comments from SimaPro Compound List

The LCAs for virgin ABS, PVC, PP, PE, SBR, EPDM, and NBR were obtained from SimaPro. SimaPro contains unit processes for many different plastics and rubbers and every effort was made to choose products similar in nature to the material produced in the PolyDyne™ process. The products evaluated and caveats for each compound specified in SimaPro were as follows:

- **EPDM rubber ETH S** - EPDM rubber ETH, original German title: Gummi EPDM. Total aggregated system inventory. This is a single results record of the similar unit process. Small differences can occur due to rounding. As representative for rubbers EPDM rubber is modeled. It consists of 35% elastomer, 44% carbon black, 7 % chalk and quartz compounds and 15 % plasticizer. These components are made into a granulate, then extruded and vulcanized. Elastomer and plasticizer modeled as PE, chalk and quartz compounds are modeled as limestone. Sulfur is not included. Vulcanisation is modeled using a salt bath (70% KNO₃, 30% LiNO₃).
- **SBR I** - LCA for the production of SBR. Copolymer of butadiene and styrene with ratio 77/23, usually reinforced with carbon black.
- **SBR FAL** - Data for the material and energy requirements and process emissions for the production of 1000 pounds of styrene butadiene rubber (SBR). Average USA technology, late 1990's. (1000 pounds= 453.59 kilograms)
- **NBR I** - Copolymer of acrylonitrile and butadiene, ratio 30/70%. Poor data averaged for 1992.
- **ABS I** - LCA for the production of 1 kg of ABS in Europe. Average data for 1995.
- **ABS A** - Production of ABS (acrylonitrile-butadiene-styrene-copolymer). ABS is a two phase polymer consisting of a glassy matrix of styrene-acrylonitrile copolymer and the synthetic rubber styrene-butadiene copolymer. Data based on information from 5 plants in Germany, Italy and the Netherlands, producing 360 000 tonnes in 1995.
- **PE (weighted average B250)** - Weighted average production of polyethylene (HDPE, LDPE, LLDPE) granulates in Europe according to APME data from 36 companies. Data account for production of 4.5 Mt PE, which is half of the total Western European production. The average energy-use of the production processes including feedstock is 85.8 MJ/kg (range: 69-107). Transports for imports of polymers into Switzerland are not included.
- **PP A** - Production of polypropylene resin (PP). Data from 15 plants in Austria, Belgium, Finland, the Netherlands, Norway, Portugal and the UK, producing 1,580,000 tonnes (1992-1993). Total European production in 1997: 6,474,000 tonnes.

- **PP I** - LCA for the production of polypropylene granulate. Average for Europe 1992-94.
- **PVC (B250)** - Weighted average production (block, emulsion, suspension) of polyvinyl chloride in Europe according to APME. Data account for a total production of 2.2 Mt/yr in 14 companies. The average energy-use of the production processes including feedstock is 66.8 MJ/t (range 48-89). Transports for imports of polymers into Switzerland are not included.
- **PVC I** - Inputs and outputs associated with the production of 1 kg suspension (general purpose) PVC granulate in Europe averaged over all the polymerization processes.

3.3. Competitor Compounds' Lifecycle GHG Emissions and Energy Requirements

The GHG emissions for the plastics and rubbers of interest are shown in Table 3-3 and are derived from SimaPro. Process CO₂ emissions varied from 1.0 to 3.1 lb/lb product (2.1 lb/lb product arithmetic average). Since the life cycle assessment CO₂ emissions for recycled rubber are 0.79 lb CO₂ /lb product, net CO₂ savings varied from 0.2 to 2.3 lb/lb product (1.3 lb/lb product arithmetic average). N₂O and CH₄ emissions are included in the table but not compared to the recycled PolyDyne™ rubber because they are negligible even when using the appropriate 100 year global warming potential multipliers. These values are substantially lower than those found in *A National Approach to Waste Tyres* as shown in Table 3-4 and Table 3-5, but similar to the values in reported in *Life Cycle Assessment of a Car Tire* from the Continental Tire Company as shown in Table 3-6. Since the SimaPro numbers are the most conservative, they are used in subsequent calculations.

Table 3-3.
Sima Pro Virgin Compound GHG LCA Emissions and PolyDyne™ CO₂ Net Savings

Compound	CO ₂ Released (lb/lb) ¹⁰	N ₂ O Released (lb/lb)	CH ₄ Released (lb/lb)	Net CO ₂ Savings (lb/lb)
EPDM rubber ETH S	3.0	8.1E-05	9.9E-03	+2.2
SBR I	1.3	NA	NA	+0.5
SBR FAL	2.3	3.7E-06	1.4E-02	+1.5
NBR I	1.0	NA	9.0E-07	+0.2
ABS I	3.1	NA	1.2E-02	+2.3
ABS A	3.1	NA	1.2E-02	+2.3
PE (granulate average B250)	2.2	6.0E-06	4.2E-06	+1.4
PP A	1.9	NA	NA	+1.1
PP I	1.1	NA	NA	+0.3
PVC (B250)	1.9	6.8E-06	5.7E-03	+1.1
PVC I	2.0	NA	7.6E-03	+1.2

¹⁰ Based on data from SimaPro.

Table 3-4 GHG LCA Emissions and Manufacturing Energy from Australia Study

Material Production	Material Energy (MJ/kg)	Greenhouse (kgCO2/kg)
Natural rubber	8	0.4
Synthetic rubber	110	5
Carbon black	125	5.7
All other additives	100	8.2
Fabric	45	2.1
Steel tyre cord	36	3.2
Mfg (per kg tyre)	11.7	1.86

Table 3-5 Energy and GHG per kg of Tire from Australia Study¹¹

	MJ/kg tire	kgCO2/kg tire
Natural rubber	1.2	0.1
Synthetic rubber	38.0	1.7
Carbon black	28.2	1.3
All other additives	10.0	0.8
Fabric	2.6	0.1
Steel tyre cord	6.2	0.6
Manufacture	12.3	1.9
Transport of materials	4.0	0.3
Total per kg tire	103.0	6.8

Table 3-6 Energy and GHG per kg of Tire from Continental LCA¹²

	MJ/kg tire	CO2e/kg tire
extraction	32.5	2.2
transport	2.5	0.2
manufacturing	16.0	1.1
Total per kg tire	50.9	3.5

¹¹ *A National Approach To Waste Tyres*, Atech Group, 2001. pages 34 Tables 6.9 and 6.10

¹² *Life Cycle Assessment of a Car Tire*, Continental Tire Company, 1999, pages 6, 12 and 15.

Gross energy requirements including feedstock energy and process energy are shown in Table 3-7 and in similar fashion to CO₂ estimates, gross energy requirements can vary to a large degree depending on system efficiencies, magnitude of the process, type of energy used, and raw materials. Table 3-8 compares raw (gross) energy requirements determined from SimaPro to other values found in literature. Although the values can vary by as much as 88 percent, the values are still on the same order of magnitude.

Table 3-7.
Virgin Plastic/Rubber Gross Energy Requirements

Compound	Energy Required (BTU/lb)¹³	Equivalent Crude Oil (gal/lb)	Equivalent Crude Oil Savings (gal/lb)
EPDM rubber ETH S	44,000	0.15	+0.11
SBR I	33,000	0.12	+0.08
SBR FAL	69,000	0.24	+0.20
NBR I	36,000	0.13	+0.09
ABS I	37,000	0.13	+0.09
ABS A	38,000	0.13	+0.09
PE (granulate average B250)	34,000	0.12	+0.08
PP A	33,000	0.12	+0.08
PP I	34,000	0.12	+0.08
PVC (B250)	26,000	0.09	+0.05
PVC I	18,000	0.06	+0.02

¹³ Based on data from SimaPro.

**Table 3-8.
Gross Energy Requirement Comparison (BTU/lb product)**

Compound	SimaPro	Patel et al. ¹⁴	Kindler/Nikles ¹⁵	APME/BUWAL ¹⁶	OIT ¹⁷	Worrell et al. ¹⁸	Lawson ¹⁹
Polyethylene	34,000	28,000	30,000-31,000	36,000	56,000	29,000	NA
Polyvinyl chloride	22,000	23,000	23,000	NA	NA	23,000	34,000
Synthetic rubber	51,000	28,000	NA	NA	NA	33,000 (SBR)	47,000

¹⁴ Patel, Martin. Table 4.7: Overview of GER data from various sources (Kindler, Nikles 1980; APME 1993-1998; BUWAL 232; OIT; Worrell et al. 1994). *Closing Carbon Cycles*. 1999.

¹⁵ Kindler, H. and Nikles, A. *Energieaufwand zur Herstellung von Werkstoffen – Berechnungsgrundsätze und Energieäquivalenzwerte von Kunststoffen*. *Kunststoffe* 70 (1980) 12, pp. 802-807.

¹⁶ APME, Association of Plastics Manufacturers in Europe. *Eco-profiles of the European plastics industry*. Prepared by Dr. I. Boustead for the APME, various reports on different types of plastics, Brussels, 1993-1998.

¹⁰ BUWAL, Bundesamt für Umwelt, Wald und Landschaft. *Okobilanz von Packstoffen*. Schriftenreihe Umwelt Nr. 132, Bern 1991.

¹⁷ OIT, Office of Industrial Technologies. *Energy, Environmental, and Economics (E3) Handbook*. Energy Efficiency and Renewable Energy Network (EREN), U.S. Department of Energy (DOE). <http://www.oit.doe.gov/E3handbook/>, Version vom 24.4.98.

¹⁸ Worrell, E., van Heijningen, R.J.J., de Castro, J.F.M., Hazewinkel, J.H.O., Beer, J.G. de, Faaij, A.P.C., Vringer, K. *New gross energy-requirement figures for materials production*. *Energy*, Vol. 19, No. 6, pp. 627-640. Elsevier, 1994.

¹⁹ Lawson, B. *1996 Building materials, energy and the environment: Towards ecologically sustainable development*. RAI, Canberra. [Online]. Available: <<http://www.greenhouse.gov.au/yourhome/technical/fs31.htm>>. [cited June 2007].

4. Conclusions/Recommendations

Greenhouse gas Life Cycle Assessments were compiled for the Lehigh PolyDyne™ production facility and for the production of a few compounds of interest using SimaPro software. Based on the LCAs, the following conclusions can be drawn:

- Lehigh's Scope 1, 2, and 3 CO₂ emissions are 0.53 lbs CO₂/lb of product when using the liquid nitrogen emission factor obtained from SimaPro, which was lower than the emission factor used for previous calculations in Phase 1 of this project. The life cycle assessment CO₂ emissions are 0.79 lbs CO₂/lb of product produced when estimates of electricity and diesel preproduction emissions are included for the scrap tire shredding process.
- Based on CO₂ emissions and gross energy requirements, the PolyDyne™ process requires 0.04 gallons of equivalent crude oil to produce one pound of product.
- The arithmetic average CO₂ emissions for virgin plastics/rubber based on SimaPro data are 2.1 lbs CO₂/lb of product produced (ranging 1.0 – 3.1 lb/lb). By recycling scrap tires and substituting PolyDyne™ rubber for virgin plastics/rubber, emissions can be reduced by 62 percent (1.3 lbs CO₂/lb of product using an arithmetic average). Other literature sources give higher values of emissions savings, so this is a conservative estimate.
- The arithmetic average equivalent crude oil savings achieved by using recycled rubber in place of virgin rubber/plastic is 0.09 gal/lb of product produced. Most of the energy savings are attributed to the reuse of feedstocks (energy locked up in the product).
- The scope of this study was to compare the PolyDyne™ process CO₂ emissions and energy requirements to those of select compounds of interest. The values stated above are for rough comparison purposes only and are based on industrial averages and many assumptions. LCA and GHG emission calculation is a nascent, inexact science, especially in the United States. Most data are obtained from historical averages in Europe and may not necessarily be indicative of processes in the United States but are the best indicators given the available data.