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Center for Sustainable Systems
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Nomenclature and Glossary

ABBREVIATIONS	
General	
AA	Aluminum Association
ANL	Argonne National Laboratory
ACC	American Chemistry Council
BOF	basic oxygen furnace
EAF	electric arc furnace
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
HHV	higher heating value
IAI	International Aluminium Institute
LCI	life cycle inventory
LPG	liquefied petroleum gas
LHV	lower heating value
USGS	United States Geographic Survey
Emissions	
VOC	volatile organic compounds
CO	carbon monoxide
NOx	nitrogen oxides (mainly no and no_2)
PM10	particulate matter (with a diameter of 10 micrometers or less)
PM2.5	particulate matter (with a diameter of 2.5 micrometers or less)
SOx	sulfur oxides (principally so_2)
CH4	methane
N2O	nitrous oxide
CO2	carbon dioxide
CO2 (VOC, CO, CO2)	carbon dioxide total including carbon content of CO, VOC emissions converts to carbon dioxide
GHGs	greenhouse gases (reported as global warming potential in CO_2 equivalent)
Plastics	
ABS	acrylonitrile-butadiene-styrene
EPDM	ethylene propylene diene monomer
GPPS	general purpose polystyrene
HDPE	high density polyethylene
HIPS	high impact polystyrene
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
PC	polycarbonate
PET	polyethylene terephthalate
PP	polypropylene
PUR	polyurethane
PVC	polyvinyl chloride
UPR	unsaturated polyester resin

KEY TERMINOLOGY	
General	
Purchased Energy	Energy or energy carriers purchased by the raw material producers for the creation of these materials. Sometimes referred to as 'delivered energy'.
Upstream Energy	Energy consumed to extract, harvest, refine, process, and deliver purchased energy.
Primary Energy	Sum of purchased energy and corresponding upstream energy. Sometimes referred to as 'resource energy'.
Upstream Emissions	Emissions generated to extract, harvest, refine, process, and deliver purchased energy and purchased materials.
Feedstock Energy	The energy content of fuels that are typically combusted, but instead serve as inputs in the production of raw material (especially plastics).
Terms as used in GREET	
Combustion Emissions	Air emissions resulting from the combustion of fuels including fuels used to generate electricity. Upstream emissions are included in this total.
Non-Combustion Emissions	Air emissions resulting from the generation and release of substances into the air that are not directly associated with the combustion of fuels.
Total Energy	See primary energy.
Total Emissions	Sum of combustion and non-combustion emissions.

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1 Introduction

First developed in 1995 at Argonne National Laboratory (ANL), the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model quantifies the energy consumption and emissions resulting from passenger vehicle transportation in the United States over the vehicle's life cycle. The model includes fuel-cycle analysis (GREET 1.8) and vehicle-cycle analysis (GREET 2.7) to allow for a Well-to-Wheel accounting of energy consumption and air emissions for different conventional and alternative passenger vehicle systems. A schematic showing the stages covered in each component of the model is shown in Figure 1.1.

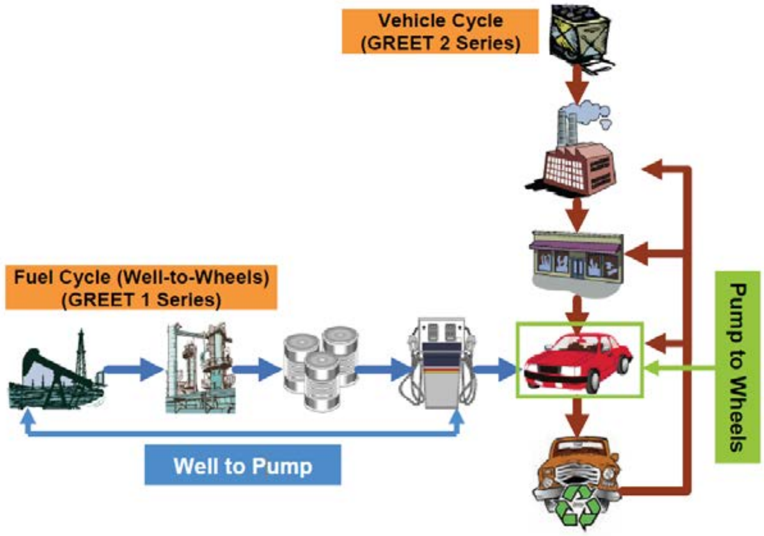

Figure 1.1: Total Energy Cycle for Transportation Technologies[1]

1.1 Project Description

The Center for Sustainable Systems (CSS) was contracted to update the raw material production data used to calculate the environmental burdens from vehicle production within the GREET model. In addition, CSS also characterized some common material transformation processes used to manufacture vehicle components.

Among the reasons for undertaking this project at this time were:

- The opportunity to update data for existing materials in the GREET model with more recent and/or higher quality data.
- The opportunity to acquire data for materials not currently found in GREET, but expected to have growing importance in the composition of vehicles in the future.
- As automobile manufacturers continue to improve use phase efficiency, the material production and manufacturing stages become more significant in determining total life cycle burdens of personal transportation. Thus representing vehicle manufacturing will become increasingly important.
- GREET data is used as a resource for other life cycle research, and thus the results of this project are expected to benefit future research.

[1] Burnham, A., Wang, M., Wu, Y. (2006) *Development and Applications of GREET 2.7: The Transportation Vehicle-Cycle Model*. Argonne National Laboratory: Argonne, IL.

1.2 Scope

1.2.1 Environmental Burdens

Consistent with GREET's current scope, the following environmental pollutants and energy resources were considered:

- **Criteria Air Pollutants:** volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter ($PM_{2.5}$ and PM_{10}).
- **Greenhouse Gas (GHG) emissions:** carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and other significant GHGs where data are available such as Sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs).
- **Energy resource consumption:** Total primary energy, fossil energy resources (e.g., petroleum), energy carriers (e.g., diesel, electricity)

1.2.2 System Boundaries

The project sought to accumulate data to represent the energy and emissions from the production of raw materials from cradle-to-gate. This was done through acquiring data on energy purchased by the raw material producers. Existing emission factors in GREET 1.8 for various combustion technologies were used to calculate the total energy and total combustion emissions. This allows the material Life Cycle Inventories (LCIs) to reflect future efficiency improvements in combustion technologies modeled in GREET 1.8. Non-combustion, process emissions (e.g., sulfur emissions from processing sulfide ores) are included in the inventory by adding these to the combustion emissions. This framework is summarized in Figure 2.1.

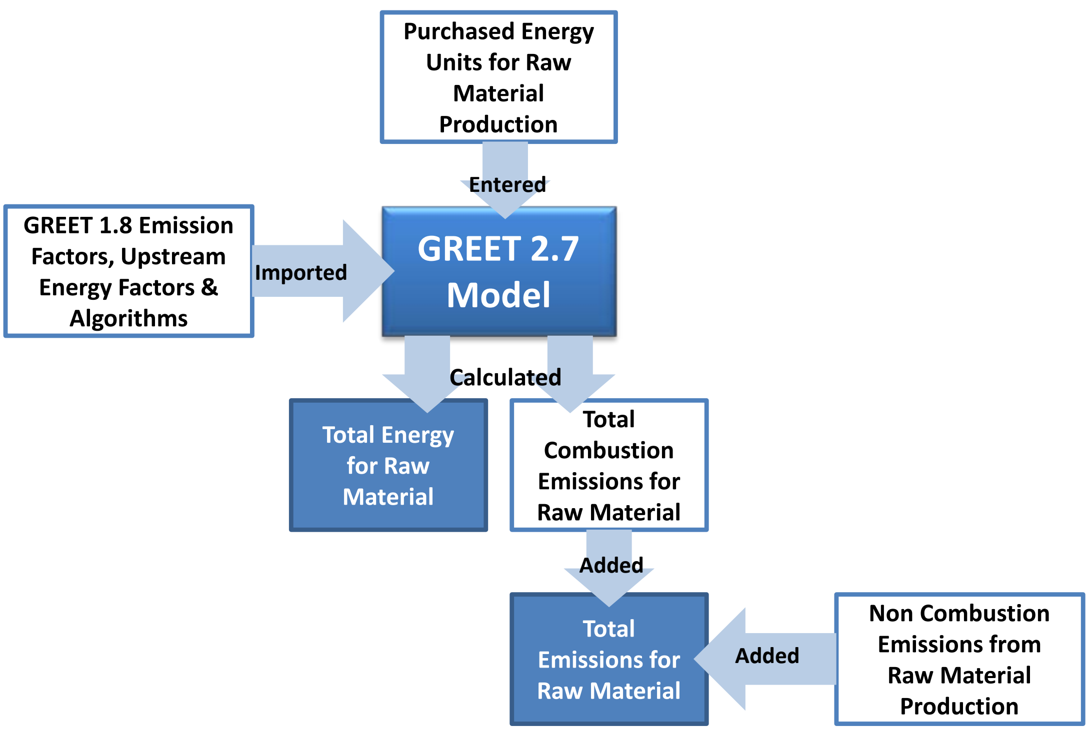

Figure 1.2: Schematic of Total Energy and Total Emissions Calculations in GREET

Transportation of energy and materials within the raw material supply chain are included when the data are available. Transportation beyond the factory gate is excluded.

1.2.3 Materials

Table 1.1 summarizes the changes being made to the material modules in GREET 2.7.

Table 1.1: Scope of Raw Materials Included within the Project

Metals	**Plastics**
Revised Materials	
Steel (Primary and Secondary) Aluminum (Primary and Secondary) Nickel (Primary) Copper (Primary)	Polypropylene HDPE Liquid Epoxy (replacing 'Polyester' in GREET)
New Materials to GREET	
	LDPE LLDPE Nylon 66 Nylon 6 Polycarbonate Polystyrene (General Purpose and High Impact) Polyvinyl Chloride Acrylonitrile-Butadiene-Styrene EPDM Epoxy Polyurethane (Rigid and Flexible Foam)

The materials currently examined in this project account for over 80% of the mass of raw material used in a conventional vehicle as modeled in GREET.

Material recycling credits are not considered, but primary and secondary sources are quantified separately for metals when the data is available.

1.2.4 Production Stages

GREET currently considers the production of metals in different production stages. Mining is modeled separately and processing of the extracted material is then modeled in one or more stages. Whenever possible, we attempted to preserve the separation of production stages and even add additional intermediate stages to the model. However, this was not always possible due to the way industry data is compiled and detail may actually be lost as a result.

1.2.5 Transformation Processes

The research team compiled and reported on existing datasets for relevant material transformation processes (e.g., stamping, casting, etc.) used in vehicle manufacturing where this data was available.

1.2.6 Geographic Scope

The geographic scope for the data is primarily North America. In cases where material production practices are similar among regions, data sets from these other regions (e.g., Europe) were used when the data are deemed to be of higher quality. Global data was also used as necessary to fill in data gaps.

1.2.7 Temporal Scope

In general, the most recent data available prior to September 2011 (the conclusion of the project) for the respective raw materials was utilized. Older data was considered in cases where the data is deemed to be more representative or more complete.

1.3 Potential Sources of Discrepancy

Every effort was made to represent the raw materials and transformation processes as accurately as possible with the GREET model, but some factors may contribute to discrepancies between the project results, existing GREET values, and other published results. These factors are summarized below:

- **Different heating values:** GREET relies on lower heating values (LHV) to calculate energy burdens while other sources prefer using higher heating values. In addition, heating values (whether higher or lower) can vary slightly among sources.
- **Limited fuel classifications in GREET:** The current GREET model relies on five main fuels and electricity to calculate total life cycle energy and emissions for each raw material. These categories are residual oil, diesel, natural gas, coal, electricity. Other published results for raw material production often have more diverse categorization schemes, which allow for more specific energy and emission factors to be applied.

  For this project, additional fuel categorizes were incorporated in the GREET raw material model spreadsheets in order to allow for more specific energy and emission factors to be used. The energy and emissions factors for these fuels were already contained in the GREET 1.8 fuel model spreadsheets. The new fuel categorization scheme is presented in Table 1.2.

Table 1.2: Fuel Categories and Fuel Assignments in GREET

Existing Categories					Proposed Additions to GREET		
Residual oil	**Diesel**	**Natural gas**	**Coal**	**Electricity**	**Crude Oil**	**LPG**	**Gasoline**
Residual Oil Heavy Fuel Oil Light Fuel Oil	Diesel Distillate Oil	Natural gas	Coal	Electricity Uranium (used in electricity generation)	Crude Oil	LPG Propane	Gasoline

  In addition, the following material-specific fuel categories were necessary in order to model materials:
  - Coke (steel)
  - Coke Oven Gas (steel)
  - Blast Furnace Gas (steel)
  - Internal Offgas from Natural Gas/Oil (plastics)

- **Ancillary material burdens:** Energy and emissions associated with ancillary materials are excluded in GREET model. In this project, lime production was modeled for steel making. Other published data may account for burdens from more ancillary materials.
- **Feedstock energy:** Feedstock energy for plastic resin production is typically included in published sources. However, it does not appear that feedstock energy was included in existing GREET due to the fact that combustion emissions are calculated as if all fuel sources are combusted. If feedstock energy was considered, a certain portion of the input fuels should have been excluded from combustion.
- **Upstream factors:** For all materials except aluminum, GREET calculates energy and emission results based on an electricity grid mix that the user can select. The default is the

average U.S. grid mix. For some industries, this grid mix may not be representative of the actual sources used to generate the electricity purchased.

- **By-product allocations:** The GREET model does not allocate energy and emission burdens to waste products that are sold to other industries outside of the raw material production system. Other published results sometimes allocate a portion of the energy consumption and resulting emissions to these waste products based on factors such as mass or economic value.

2 Methods and Results

The methods for compiling purchased energy and non-combustion emissions are discussed below. Additions or alterations to the GREET model need to incorporate these data are also presented. Total energy and emissions results were calculated using the GREET model. The results are presented in the same format as the GREET spreadsheet model. **The number of significant digits displayed should not be interrupted as an indication of precision.**

2.1 Metals

2.1.1 Steel Material Production and Transformation

2.1.1.1 Description of Process Steps

The two dominant steel production methods are described below.

Integrated Mills – These steel mills produce virgin steel product using mined iron ore although some steel scrap is usually recycled in the process as well. The steps in producing steel in an integrated mill are summarized below:

- Limestone and Lime – Limestone is extracted and processed into lime. Both are used as fluxes to capture impurities in the steel making process.
- Mining – Iron-bearing rock is extracted out of the earth.
- Ore Pelletizing -- The rock is crushed into fine particles, and the iron ore within the rock is separated out using magnets. This powder of iron ore is heated to form iron ore pellets.
- Sintering –Sinter is formed from steelmaking waste products such as iron ore powder, coke breeze, and limestone or other flux materials. These ingredients are fused together with heat and then crushed into smaller pieces to be added to the blast furnace.
- Coke Production – Coal is crushed and baked in ovens to remove impurities leaving a high-carbon fuel for steel making.
- Blast Furnace – Iron ore pellets, sinter, and coke are added to the blast furnace. Limestone helps remove impurities, which float to the top of the furnace and are removed as slag. The coke combusts in the furnace and the resulting product is liquid pig iron.
- Basic O2 Processing – Liquid iron is added to the basic oxygen furnace along with oxygen to reduce the carbon content of the iron, thus converting it into steel.
- Rolling – Steel is cast into steel slabs and rolled through a series of rollers into steel sheets. The rolling process begins with heated steel (hot rolling), but further rolling is often done on cold sheet steel (cold rolling) to further reduce thickness and achieve desirable material characteristics.
- Galvanizing – A thin zinc coating is often applied to cold rolled steel in order to prevent corrosion.

Mini Mills – In these mills, steel scrap is fed into a furnace and is melted by means of an electric arc from an electrode lowered into the furnace.

While both of these production approaches can be used to produce a variety of steel material, integrated mills typically specialize in producing flat rolled products such a sheet steel and mini-mills tend to specialize in the production of long products such as rod and bar stock. Thus, steel production was represented using the appropriate mill type for each steel form.

Steel sheet products are often manufactured into auto parts by means of a stamping press equipped with a die that transforms the material into the desirable shape. Steel bar and rod may be machined into necessary forms, but these processes were not explored in this project. Scrap steel processing activities were not modeled in this project. Steel scrap input in the BOF is assumed to be composed of internally generated scrap. No energy burdens are assigned to this scrap at this stage. Instead, the scrap generated in subsequent unit processes reduces process yields (% metal output/metal input), which increases the amount of liquid steel demanded from the BOF to produce sheet steel product. The production of steel is summarized in flow chart in Figure 2.1.

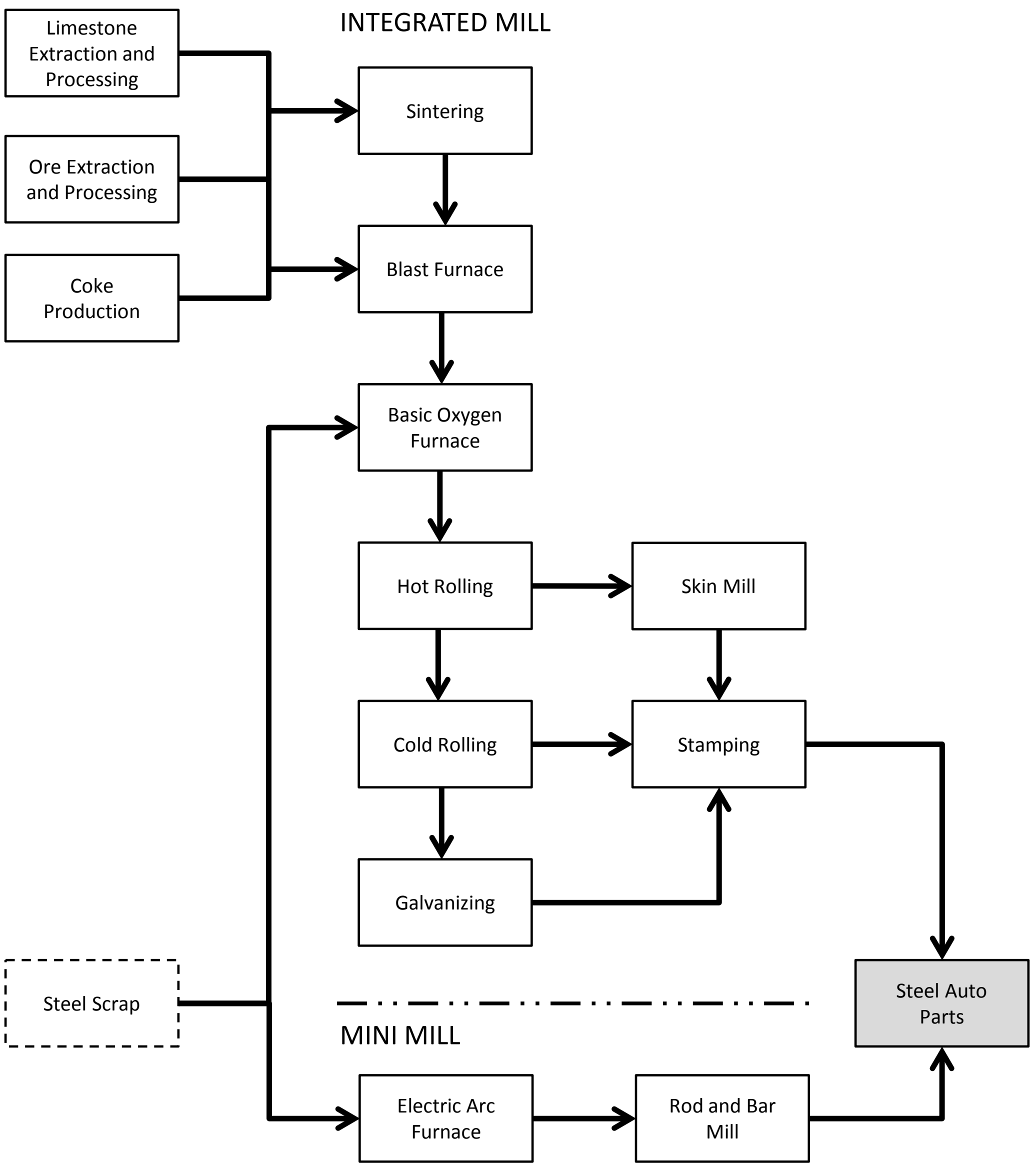

Figure 2.1: Steel Production Flowchart

2.1.1.2 Data Source(s)

Data from the Athena Sustainable Materials Institute served as the basis for the results presented in this project. The data is detailed in *Cradle-To-Gate Life Cycle Inventory: Canadian and U.S. Steel Production by Mill Type*[2]. The report represents both basic oxygen furnace (BOF) and electric arc furnace (EAF) production methods. Due to the complexity of the steel making process, the authors synthesized the data into reference plants to represent each production approach. The data represent the production of steel from the extraction of ore through the manufacture of semi-finished steel products including sheet, plate, rod, bar, and section products. The data for the production of limestone and lime are given as well.

[2] Athena Sustainable Materials Institute (2003) Cradle-To-Gate Life Cycle Inventory: Canadian and U.S. Steel Production by Mill Type. Based on reports by Markus Engineering Services.

Data Quality
The Athena report is a revision of separate BOF and EAF reports which were produced 1993-1994. The extent of the revisions and the time period of the primary data collection were not reported. Energy and material data is presented by process stage.

Other Data Sources
Additional data for the project was sought from the World Steel Association (formerly the International Iron and Steel Institute). World Steel is compiling data for the production to semi-finished steel products. This data is more recent than the Athena data, but World Steel was not able to provide results with the necessary degree of detail within the timeframe of this project.

2.1.1.3 Data Preparation for GREET
Four different steel types were used to represent the steel material used for vehicle manufacturing. Each material's relative contribution to the curb weight of the vehicle is presented in Table 2.1.

Table 2.1: Mass Fraction of Steel Type in Conventional Vehicle[3]

Steel Material	Mass %
Galvanized	44.0%
EAF	26.4%
Hot Rolled	15.5%
Cold Rolled	14.1%

Steel sheet products (hot rolled, cold rolled, and galvanized) were assumed to be formed by stamping while steel from EAF processing was modeled as rod/bar stock with no further processing.

The steps for preparing the Athena data for incorporation into GREET are outline below.

1. **Synthesizing process stages:** The Athena report presents mass and energy balances for steelmaking processes. Some of these processes were combined and renamed to provide a simpler format for the GREET model. This reorganization is summarized in Table 2.2 and Table 2.3 for Integrated and Mini Mills, respectively.

Table 2.2: Integrated Mill Process Stages

GREET Process Stage	Represented Athena Process Stages
Limestone Extraction and Processing	• Limestone Extraction (for blast furnace and sinter plant) • Limestone Extraction (to make lime) • Burnt Lime Production • Dolomitic Lime Production
Ore Extraction and Processing	• Ore Exploration and Development • Hematite Ore (mining, crushing, concentrating, pelletizing) • Magnetite Ore (mining, processing)
Coke Production	• Coke Ovens
Sintering	• Sintering Plant
Blast Furnace	• Blast Furnaces

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[3] Sullivan et al. (1998) A Life Cycle Inventory of a Generic U.S. Family Sedan—Overview of Results, USCAR AMP Project. *Proceedings of Total Life Cycle Conference and Exposition*. Society of Automotive Engineers, Graz, Austria.

	• Stoves • Boilers (whole plant) • Steam to Produce Electricity (turbines/generators)
Basic O2 Processing	• BOF • Steelmaking Ladles • Caster (includes casting tundishes)
Hot Rolling Mill	• Hot Strip Mill
Skin Mill	• Skin Mill
Cold Rolling	• Cold Mill Complex (includes annealing, pickling, & cleaning)
Galvanizing	• Galvanizing Line
Stamping	• Not from Athena Data--Retained from the previous version of GREET

Table 2.3: Mini Mill Process Stages

Electric Arc Furnace	• EAF – Shapes • Ladle Metallurgy Furnace (LMF) – Shapes • Billet Caster
Rod and Bar Mill	• Rod and Bar Mill

2. **Add fuel energy by process stage:** The energy associated with the input fuels was summed for each process stage in GREET. The creation of coke, blast furnace gas, and coke oven gas were credited as negative values. Fossil fuels that were used as feedstock sources were presented separately. The following fuel categorizes were used:
    - Residual oil (included fuel oil)
    - Diesel (included gasoline)
    - Natural gas used
    - Coal
    - Electricity
    - Oil as feed
    - Natural Gas as feed
    - Coal as feed
    - Coke
    - Blast furnace gas
    - Coke oven gas

    In the 'Hematite Ore' stage in the Athena data 'Light Fuel Oil' and 'Fuel Oil' are each shown as contributing 725,225 GJ of energy toward the production of 1,870,390 tons of ore. It was assumed this value was duplicated because only 'Fuel Oil' is shown among the specific energy values. Thus, the 725,225 GJ value was represented as residual oil.

    The energy from the boiler plant was included along with the blast furnace stage; however steam from the boiler plant was used in other process stages. The portion of the fuels combusted to provide this exported steam was reported separately in the case of the rolling mills and other finishing operations. Thus, the input of combustion fuels in the boiler plant was adjusted accordingly so that these fuels were allocated to the processes in which the steam was utilized.

Tar and Benzene are by-products of the steelmaking process and are sold outside the system. These were not credited in this project.

3. **Add non-combustion emissions by process stage:** The data presented in the Athena report separated emissions into combustion and process emissions for the integrated mill. Non-combustion emissions were added together for each process stage.

   The following corrections and modifications were made to the data:
   - Emissions for 'Ore Exploration and Development' were labeled as combustion, but no fuel data was presented and thus these emissions were included as non-combustion emissions.
   - Emissions for the 'Sintering Plant' included process emissions for the wind box. It was assumed that coke oven gas was the primary fuel combusted in this operation. Thus combustion factors for coke oven gas were used to calculate the combustion emissions for the stage. These were subtracted from the wind box process emissions and the remaining emissions were included as non-combustion emissions.
   - Emissions data for mini mills were not separated between combustion and non-combustion emissions. For the 'EAF-Shape' and 'Billet Caster' stages, emission factors for the combustion of natural gas were used to calculate combustion emissions. These were then subtracted from the reported emissions, and the remaining emissions were assumed to be process emissions.
4. **Calculation of mass balance of intermediate products:** Material flows were calculated from the reference plants in the Athena report. In the case of the integrated mill, only hot rolled, cold rolled, and galvanized sheet products were modeled for GREET, thus the mass balance through the final rolling stages were adjusted to meet the desired mass portion. Figure 2.2 summarizes the flow of intermediate material through the final production stages into sheet products.

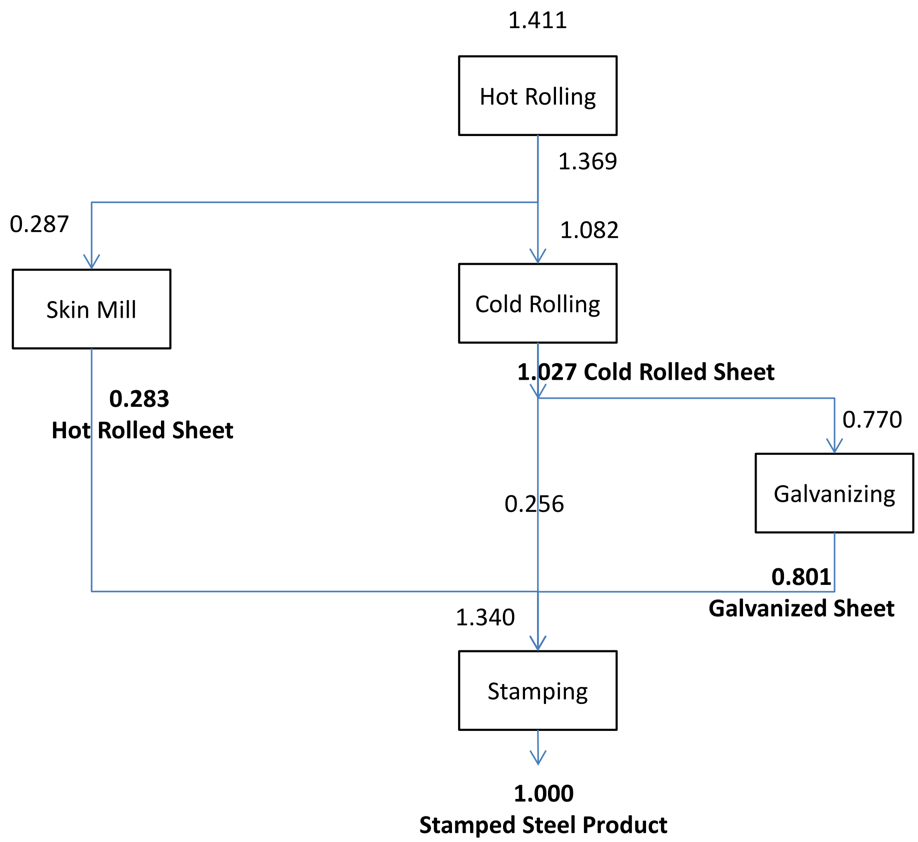

Figure 2.2: Material Flow of Intermediate Steel Products through Rolling and Stamping (per ton of steel product)

5. **Alterations to GREET model:** The previous GREET model was altered as follows:
    - Emission factors for the combustion blast furnace gas and coke oven gas were added to GREET based on factors given in the Athena report.
    - Categories for blast furnace and coke oven gas credits were added so the both the generation and consumption these gases within a process stage could be accounted for separately.
    - The calculation of total the energy from coke, coke oven gas, and blast furnace gas was summed along with coal energy for calculating the total primary coal energy consumed. The upstream energy from these coal-byproduct fuels was calculated in the same manner as coal itself based on the energy of the fuel. Credits for coke oven gas and blast furnace gas in a particular stage reduced the total energy consumed in the stage in which they were generated. The energy associated with these by-product gasses was accounted for in stages in which they were combusted.

2.1.1.4 Total Energy and Emissions Results[4]

The total energy and emissions results for steel are summarized in Table 2.4 and Table 2.5 below. Results for hot rolled sheet are also presented for comparison with the USLCI Database.

Table 2.4: Comparison of Virgin Steel Data

	Updated Values (Final Product)	Updated Values (Hot Rolled)	GREET 2.7 (Final Product)	GREET 2.7 (Rolled Steel)	USLCI Database (Hot Rolled)
Energy Use (mmBtu/ton)					
Total Energy	50.750	26.701	38.771	23.293	21.639
Fossil fuels	48.110	25.559	37.856	22.909	
Coal	34.272	20.186	24.233	16.691	
Natural gas	11.033	3.494	11.936	5.025	
Petroleum	2.804	1.879	1.688	1.193	
Total Emissions (g/ton)					
VOC	3949.152	2817.717	536.021	360.117	188.232
CO	28666.748	20727.160	108,869.120	81,120.454	22,594.331
NOx	4048.560	2042.527	3,602.296	2,237.815	2,560.439
PM10	3872.456	2165.683	14,593.847	10,632.276	
PM2.5	1424.213	857.951	6,303.381	4,627.528	
SOx	10662.420	6077.278	1,988.177	1,023.602	3,920.672
CH4	3386.972	1203.032	5,181.747	2,986.783	1,024.212
N2O	28.561	10.780	30.362	16.444	
CO2	3,911,899	2,072,497	4,587,856	3,034,020	2,060,381
CO2 (VOC,CO,CO2)	3,969,255	2,113,850	4,760,607	3,162,617	
GHGs	4,062,441	2,147,138	4,899,199	3,242,187	2,085,986

[4] Note about total energy and emissions values in this report: In order to better understand the data compiled for this project and make comparisons with the material production and processing burdens in the GREET 2.7 model and other sources, it was necessary to incorporate the data into the GREET model. Frequently, alterations to the model itself were required in order to input the data (e.g. adding additional process stages and/or fuels) to generate energy and emissions results. The values that were output from this process may differ somewhat from values in subsequent versions of the GREET model released by Argonne National Laboratory due to differences in modeling the material production and transformation itself as well as other changes to the fuel cycle portions of the model. The project results are provided for reference only.

Table 2.5: Comparison of Recycled Steel Data[5]

	Updated Values (EAF Steel)	GREET 2.7 (EAF Steel)
Energy Use (mmBtu/ton)		
Total Energy	21.108	29.337
Fossil fuels	18.901	27.564
Coal	11.455	8.281
Natural gas	7.023	18.847
Petroleum	0.423	0.436
Total Emissions (g/ton)		
VOC	927.752	202.475
CO	3707.204	5,080.603
NOx	1907.773	2,144.607
PM10	2715.878	1,653.773
PM2.5	626.808	499.548
SOx	4268.510	2,691.319
CH4	2495.758	4,449.723
N2O	21.873	28.111
CO2	1,619,186	1,928,235
CO2 (VOC, CO, CO2)	1,627,903	1,936,850
GHGs	1,696,815	2,056,470

Energy values for virgin steel are higher than previous GREET values, while the GHG totals are lower. In EAF steel, the energy and GHG results were both lower. The discrepancy is likely due to more comprehensive modeling in this project for the production of sheet steel than in the GREET 2.7 model. The ratio of GHG emissions to total energy demand for the GREET 2.7 virgin steel values is significantly higher than this project or for other published results, which might indicate a modeling error associated the emissions calculations for virgin steel in GREET 2.7.

2.1.1 Aluminum

2.1.1.1 Description of Process Stages

- Bauxite mining – Aluminum is found mainly in tropical/subtropical areas and recovered from open pit mines. Beneficiation (washing, drying, screening, etc.) is required for ores from forested areas and included in this stage.
- Alumina Production (Bayer) – Al_2O_3 (alumina) is produced by grinding bauxite then reacting it with caustic soda and calcined lime. Alumina is precipitated out of this reaction and is then calcined to remove water.
- Anode Production – For use in electrolysis, petrol coke is calcined, ground, and blended with pitch to form blocks/briquettes that are baked, and then cooled to form the anode.
- Electrolysis (Hall-Heroult) – A steel pot (acting as the cathode) is filled with a molten cryolite bath and alumina. The anode is suspended in the bath and a current is run through the circuit. Aluminum is reduced during this process and tapped out of the pot daily. Consumption of the anode results in non-combustion SO_X and PFC emissions.
- Ingot Casting – Molten metal is transferred from steel pots into a holding furnace, where its composition is altered to form the desired alloy. Fluxing the molten metal with chlorine/nitrogen or carbon monoxide/argon/chlorine removes impurities and gas content. An in-line filter removes any oxides that have formed during the processing. The metal is then cast into an ingot and cooled.

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[5] See footnote 4 on page 12

2.1.1.2 Data Source(s)

The Aluminum Association (AA), a U.S. based aluminum industry group, sources primary production data from the International Aluminum Institute (IAI) surveys. The Aluminum Association published a life cycle assessment in 2010 for the aluminum can industry that addressed primary and secondary aluminum production in the United States[6]. This AA (2010) report is intended to be representative of 2006 North American industry data and was prepared by PE Americas.

Because the AA (2010) report was specific to the aluminum can industry which has particular recycling procedures that are not necessary representative of aluminum recycling in general, another source was needed to for an accurate representation of secondary aluminum production. In 1998, the Aluminum Association published a report entitled “Life Cycle Inventory Report for the North American Aluminum Industry” (AA 1998). This LCI provides information from 1995 as part of the United States Automotive Materials Partnership (USAMP) initiative. This source was deemed to be the best available data for secondary aluminum production and aluminum transformation processes.

The GREET stages of Bauxite Mining, Alumina Production (Bauxite Refining), Electrolysis (Alumina Reduction), and Aluminum Melting and Casting were updated with data from AA (2010). The ‘Anode Production’ stage is new to GREET.

Data Quality

No transportation or upstream data is included in the AA datasets, so the system boundary is around the facility only.

Other Data Sources

The International Aluminium Institute (IAI) produced a life cycle inventory documenting worldwide primary aluminum production in September 2007 using 2005 inventory data.[7] The IAI results cover the following percentages of primary aluminum production: 85% Africa, 87% North America, 24% Latin America, 14% Asia, 78% Europe, 100% Oceania. Data for China is not available. This data source was not used due to the fact that more recent data from the IAI was used to inform the 2010 AA LCA. Additionally, the IAI report intends to characterize worldwide aluminum production, while the AA report focuses on North American production. Also, industry contacts were familiar with the AA report and recommended it as the best available data.

2.1.1.3 Data Preparation for GREET

Primary Aluminum Energy

1. **Calculate purchased energy values by fuel:** AA (2010) data given in physical units of purchased energy. GREET heating values used to convert to mmBtu/ton.
2. **Allocation to fuel categories:** Heavy fuel oil is assumed to be residual oil and hard coal is assumed to be “coal” for AA(2010) data for the purposes of input into GREET.
3. **Inputting grid mix for Hall-Heroult process:** Grid mixes reported by AA are input into “user-defined” grid mix; GREET uses this as the electricity mix for Hall-Heroult process. This mix is shown in Table 2.6. Electricity mix for other process stages is assumed to be GREET’s U.S. mix.

[6] Aluminum Association (2010) http://www.aluminum.org/Content/ContentFolders/LCA/LCA_REPORT.pdf

[7] International Aluminum Institute (2007) Life Cycle Assessment of Aluminium: Inventory Data for the Primary Aluminium Industry – Year 2005 Update. http://www.world-aluminium.org/UserFiles/File/LCA.pdf

Table 2.6: Electricity Grid Mix Input in GREET Model for Hall-Heroult Process

Generating Source	Percentage
Hydropower	69.4%
Coal	29.7%
Oil	0.0%
Natural Gas	0.6%
Nuclear	0.3%

Primary Aluminum Non-Combustion Emissions

1. **Modeling SO_2 from anode production:** AP-42 is the primary compilation of EPA's emission factor information. The most recent edition[8] was published in 1995. This methodology was used to model SO_x emissions and is summarized below:

   AP-42 Equations (SO_x emissions)

   Anode baking furnace, uncontrolled SO_2 emissions (excluding furnace fuel combustion emissions):

   $$40(C)(S) \times (1 - 0.01K)\ lbs/ton$$

   Prebake (reduction) cell, uncontrolled SO_2 emissions:

   $$0.4(C)(S)(K)\ lbs/ton$$

   where:
   C = Anode consumption* during electrolysis, lb anode consumed/lb Al produced
   S = % sulfur in anode before baking
   K = % of total SO2 emitted by prebake (reduction) cells.
   **Anode consumption weight is weight of anode paste (coke + pitch) before baking.*

   Inputs to AP-42 Equations:
   C = 0.446 kg anode/kg Al from DOE EERE 2003[9]
   S = 3% according to AP-42 (this assumes use of Eastern U.S. coal)
   K = 21%, BCS reports 21% of pitch to be volatilized, it is assumed that the same distribution of sulfur will be lost during baking (anode production)

2. **CO2 emissions:** Emissions data from the DOE EERE 2003 report was used to model CO_2 emissions from the anode production and consumption process stages.

3. **PFC emissions:** IAI reported emissions for CF_4 and C_2F_6 from reporting facilities for 2009 and used Global Warming Potentials from the IPCC 2nd Assessment.[10] IAI estimates Chinese industry

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[8] U.S. EPA (1995) AP-42, Compilation of Air Pollutant Emission Factors. http://www.epa.gov/ttnchie1/ap42/
[9] U.S. DOE EERE (2003) U.S. Energy Requirements for Aluminum Production - Historical Perspective, Theoretical Limits and New Opportunities. Based on report by BCS, Inc. http://www.secat.net/docs/resources/US_Energy_Requirements_for_Aluminum_Production.pdf
[10] IPCC (2007) Fourth Assessment on Climate Change: Table 2.14 (Errata) http://www.ipcc.ch/publications_and_data/ar4/wg1/en/errataserrata-errata.html

emissions and reports the global emission factor in units of kgCO_2e/ton Al. This is then converted from metric units and input into GREET. The IAI publishes PFC emission data on an annual basis.[11] This data is presented in Table 1.1Table 2.7.

Table 2.7: PFC Emissions during Primary Aluminum Production

	IAI (2009)	Units
CF_4	0.069	kg/ton Al
GWP - CF_4	7,390	CO2eq
C_2F_6; R116	0.008	kg/ton Al
GWP - C_2F_6	12,200	CO2eq
Total PFCs	535	kgCO2e/ton Al

Secondary Aluminum

Secondary Aluminum data is sourced from AA (1998).[12] All values are in the form of purchased energy and converted to mmBtu/ton. Because the report did not provide data on scrap processing, therefore, only the remelting/casting stage is considered. "Scrap Preparation" and "Al Recycling" stages were retained from previous GREET model.

Transformation Processes

Transformation stages were defined as those coming after the "Ingot Casting" stage in the AA (1998) study. All values are in the form of purchased energy and converted to mmBtu/ton. The transformation process stages included were:

- hot rolling, cold rolling, and stamping (referred to collectively as 'wrought aluminum')
- extrusion
- shape casting

Stamping data was not present in the AA report, and thus the existing stamping data in GREET as retained. According to the AA study, aluminum use for automotive applications is 73.8% cast aluminum, 22.8% extruded aluminum, and 3.4% rolled aluminum.

Table 2.8, Table 2.9, and Table 2.10 show total energy and emissions results using the project values. Given that the reported roll-up inventory values for bauxite for each type of aluminum product were the same as those for prime ingot in the dataset, it was assumed there were no material losses occurring during these unit processes in order to calculate the values in these tables. An alternative mass input-output ratio could be calculated by assuming that manufactured scrap generated during each is recycled within each unit process. Thus, the mass of the prime ingot entering into these transformation stages would be the difference between the "metal" input and the "manufactured scrap". This approach would increase the energy and emissions values by 2.1% for wrought aluminum, 21.2% for cast aluminum, and 0.5% for extruded aluminum product.

[11] IAI (2010) Results of the 2009 Anode Effect Survey. http://www.world-aluminium.org/Sustainability/Environmental+Issues/Greenhouse+gases/PFCs

[12] AA (1998) Life Cycle Inventory Report for the North American Aluminum Industry. Based on USAMP LCI methodology developed by Roy F. Weston, Inc.

2.1.1.4 Total Energy and Emissions Results[13]

Table 2.8: Total Energy and Emissions Results for Wrought Aluminum (per ton)

	Updated Values	GREET 2.7	Aluminum Assoc. (aluminum ingot)
Energy Use (mmBtu/ton)			
Total Energy	164.955	157.507	133.256
Fossil fuels	112.681	119.724	
Coal	75.912	61.487	
Natural gas	24.849	41.381	
Petroleum	11.920	16.855	
Total Emissions(g/ton)			
VOC	924.751	1,018.729	
CO	2,824.190	3,396.301	
NOx	12,502.462	13,428.240	2,013.540
PM10	29,411.160	31,975.284	8,308.120
PM2.5	11,591.450	13,539.925	
SOx	43,049.522	34,351.349	20,207.960
CH4	14,540.617	16,319.137	
N2O	118.043	126.263	
CO2	12,937,641	10,574,404	
CO2 (VOC, CO, CO2)	12,944,961	10,578,253	
GHGs	14,183,513	11,023,858	10,031,420

Table 2.9: Total Energy and Emissions Results for Cast Aluminum (per ton)

	Updated Values	GREET 2.7	Aluminum Assoc. (aluminum ingot)
Energy Use (mmBtu/ton)			
Total Energy	115.352	132.856	133.256
Fossil fuels	78.414	96.572	
Coal	50.612	54.477	
Natural gas	19.325	26.210	
Petroleum	8.478	15.885	
Total Emissions(g/ton)			
VOC	637.742	843.946	
CO	1960.924	2,850.783	
NOx	8657.103	11,390.999	2,013.540
PM10	20542.094	30,659.443	8,308.120
PM2.5	8204.027	13,150.997	
SOx	29883.924	31,947.068	20,207.960
CH4	10269.891	12,642.084	
N2O	80.990	99.560	
CO2	8,964,457	8,820,725	
CO2 (VOC, CO, CO2)	8,969,526	8,827,835	
GHGs	9,859,002	9,173,556	10,031,420

[13] See footnote 4 on page 12

Table 2.10: Total Energy and Emissions Results for Extruded Aluminum (per ton)

	Updated Values	GREET 2.7	Aluminum Assoc. (aluminum ingot)
Energy Use (mmBtu/ton)			
Total Energy	111.635		133.256
Fossil fuels	74.604		
Coal	51.267		
Natural gas	14.844		
Petroleum	8.493		
Total Emissions(g/ton)			
VOC	613.999		
CO	1891.841		
NOx	8415.892		2,013.540
PM10	20663.393		8,308.120
PM2.5	8229.564		
SOx	30014.169		20,207.960
CH4	9519.356		
N2O	76.862		
CO2	8,767,493		
CO2 (VOC, CO, CO2)	8,772,380		
GHGs	9,641,862		10,031,420

The reduction in Total Energy relative to previous GREET values is likely due to industry efforts to increase efficiency and decrease GHG emissions. Industry reports a higher total energy due to their use of GaBi 4.3 to calculate Total Energy. Discrepancy in SO_x emissions between industry and GREET is likely due to emissions control technology that is not taken into account by AP-42. Increased GHG emissions from previous GREET findings is likely due to the inclusion of PFCs not accounted for previously in GREET.

2.1.2 Nickel

2.1.2.1 Description of Process Stages

- Mining – This stage includes all processes up to point of delivery to the "Beneficiation" process. The inventory accounts for both surface and underground mining.
- Beneficiation – Nickel ore undergoes crushing, grinding and flotation and leaves this stage as nickel concentrate for use in "Primary Extraction."
- Primary Extraction – Hydrometallurgical and pyrometallurgical processes convert nickel concentrate into nickel matte (a.k.a. smelting). Facilities using both processes were modeled and accounted for using a weighted average of the primary extraction facilities who reported.
- Refining – Nickel matte undergoes crushing, leaching, separation, and electrolysis to form the final nickel product.

2.1.2.2 Data Source(s)

The Nickel Institute provides life cycle data through its website[14] that was compiled by Ecobalance, Inc. The report was published in 2000 based on 1998 data. This study accounted for 87% of Western world nickel production and 55% total world nickel production. Currently, Russia, Indonesia, and the

[14] Nickel Institute (2000) http://www.nickelinstitute.org/index.cfm?ci_id=205&la_id=1 Accessed June 8, 2011.

Philippines are the top three nickel producing countries according to USGS, but they are not included in the Nickel Institute report.

More than 75% of primary nickel production energy use is due to smelting and refining. Therefore, overall energy consumption of nickel production is highly dependent on the grid mix of the producing country. According to USGS, about half of U.S. imports are currently from Canada. Since this data encompasses the majority of Western world production in 2000, it should be representative of the majority of North American nickel consumption.

Data Quality

For this NI (2000) study, purchased energy values are not given. Instead results are aggregated with upstream energy and presented as primary energy values.

Energy and emissions attributed to capital equipment (i.e., building energy, transport of steel/concrete) are assumed to be negligible, less than 1%. Human activities involved in nickel production (e.g., driving to/from work, societal impacts, etc.) are neglected.

The Nickel Institute acknowledges that this data is not the best representation of 2011 production due to a change in ore profile (more lateritic, less sulfidic) and new production facilities (using different process technologies). However, they are unable to identify any other possible data sources. This data is from a 1998 facility-level survey and is intended to be representative of 2000 technology. When 1998 data was not available, a previous year's data was used as long as production processes were similar. Missing production data is ignored in weighted average results; the collected data (87%) is presumed to be representative of Western world production.

Secondary data are used to model upstream materials production (e.g., fuel, auxiliary materials, electricity, etc.), transportation, and any other modeling or production data within the study boundaries not attainable by nickel production facilities. The secondary data sources include:

- Ecobalance's database, DEAM[15]
- Engineer calculations
- Bibliographic sources

Other Data Sources

A secondary and possibly more reliable data source is available from Matthew Eckelman, a post-doc at Yale's Center for Industrial Ecology. He worked with the Nickel Institute to develop a facility-level greenhouse gas emissions assessment of the global Nickel industry. His paper[16] was published in Resources, Conservation, and Recycling in 2010 and is able to provide data. Unfortunately, he could not provide the data in time to include in this project.

[15] Ecobilan Data for Environmental Analysis and Management. https://www.ecobilan.com/uk_deam.php

[16] Eckelman, Matthew (2010) Facility-level energy and greenhouse gas life-cycle assessment of the global nickel industry. http://www.sciencedirect.com/science/article/pii/S0921344909001852

2.1.3 Data Preparation for GREET

1. **Compile energy values:** Primary nickel production process stages (mining, beneficiation, primary extraction, refining) are separated into electricity, energy, upstream materials, and transportation components. The Nickel Institute only provides Total/Primary Energy values.
2. **Units conversion:** The Nickel Institute reports the mass of Coal, Oil, Natural Gas, Uranium used in primary nickel production. This data is converted to units of mmBtu/ton using GREET heating values.
3. **Determination of grid mix:** The percentage of fuels allocated to electricity for each process stage is summed; this total is used to determine the electricity grid mix. This mix is input into GREET for the purposes of using Excel Solver to determine delivered energy values.
4. **Allocating energy in mining:** For the purposes of calculating the electricity grid mix, 50% of energy used in the mining stage is assumed to be in the form of electricity.
5. **Non-combustion emissions:** No data were available to model, thus GREET2.7 values were used.
6. **Purchased energy calculation:** Because the Nickel Institute reported only total/primary energy, Excel Solver was used to back-calculate purchased energy through the GREET model. The method is described below:
    - All purchased fuels are to be greater than zero.
    - Coal, natural gas, and petroleum total energy values are set equal to reported values. Lower bounds are placed on the 5 purchased energy cells to insure the solution does not result in negative energy values for purchased fuels. Excel solver seeks to get as close to the reported total energy value as possible. See Figure 2.3 below.
    - Inputs were placed into Rows 28-32 and the Solver function attempted to get "Total Energy" (Row 28) as close to 181.836 mmBtu/ton as possible, while constraining Coal, Natural Gas, and Oil to be values in the Table 2.11 below.
    - Note: Uranium was not input as a constraint, because it is not a fuel currently present in the GREET model
    - Rows 23-27 were designated as the variable cells that Solver could change in order to achieve its objective. These are the purchased energy cells and the resulting values that Solver determined are presented in Table 2.12.

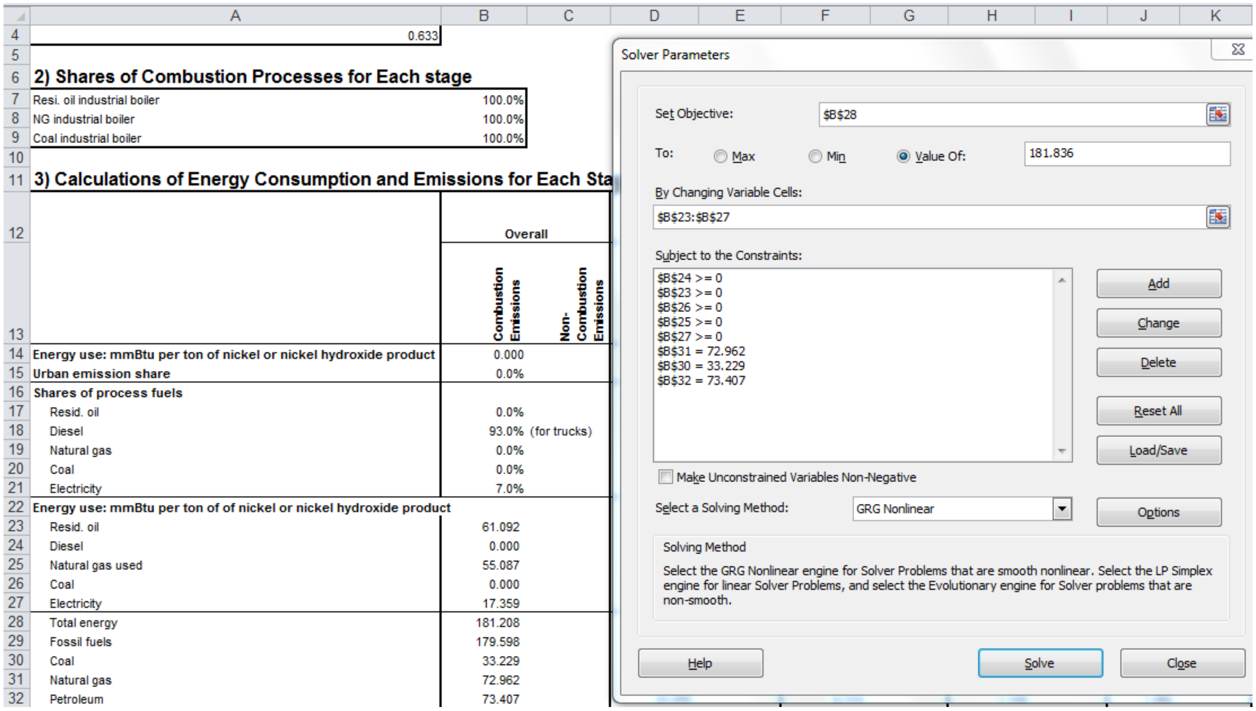

Figure 2.3: Screenshot of Excel Solver Setup Used for Purchased Energy Calculation

Table 2.11: Total Energy for Nickel Production Input into Excel Solver

	Overall	Mining	Beneficiation	Primary Extraction	Refining
Coal	33.229	0.997	1.661	22.596	7.975
Natural Gas	72.962	1.459	0.730	50.344	20.429
Oil	73.407	1.468	1.468	68.268	2.936
Residual Oil					
Uranium	2.238	0.045	0.045	0.716	1.455
Electricity					
Total - Nickel Institute	181.836	3.969	3.904	141.924	32.796

Table 2.12: Purchased Energy Outputs from Excel Solver for Nickel Production

	Overall	Mining	Beneficiation	Primary Extraction	Refining
Coal					
Natural Gas	55.087	1.000	0.119	37.372	16.547
Oil					
Residual Oil	61.092	1.136	0.972	58.700	1.655
Uranium					
Electricity	17.359	0.528	0.878	11.600	4.316
Total - GREET	133.537	2.663	1.969	107.672	22.518

"Nickel Ore Mining" and "Nickel Production" from GREET model have been disaggregated into the four process stages defined above. "Recycled Nickel Production", "Nickel Hydroxide Production", and "Recycled Nickel Hydroxide Production" from GREET have ***NOT*** been updated due to lack of reliable data sources found.

2.1.3.1 Total Energy and Emissions Results[17]

Table 2.13 shows total energy and emissions results using updated values.

Table 2.13: Total Energy and Emissions Results for Primary Nickel (per ton of wire)

	Updated Values	GREET 2.7 in GREET	Industry Source Nickel Institute
Energy Use (mmBtu/ton)			
Total Energy	181.208	127.174	181.836
Fossil fuels	179.598	113.634	179.598
Coal	33.229	63.335	33.229
Natural gas	72.962	34.306	72.962
Petroleum	73.407	15.993	73.407
Total Emissions(g/ton)			
VOC	1187.585	917.893	1995.806
CO	3961.952	2760.498	33565.835
NOx	18642.194	11830.619	47173.606
PM10	9967.683	13507.499	35380.205
PM2.5	4283.212	4201.556	
SOx	634678.561	633829.737	878154.828
CH4	22238.973	14859.787	25401.173
N2O	147.424	130.384	1179.340
CO2	13,220,797	10,291,549	12,405,751
CO2 (VOC, CO, CO2)	13,225,287	10,298,747	12,464,718
GHGs	13,825,194	10,709,097	13,451,191

Industry and Updated total energy values agree because purchased energy was back-calculated to be input into the GREET model. The intention was to get the Updated values to closely match the total energy reported by industry. The emissions do not agree, likely because there are non-combustion emissions that we were not able to disaggregate and therefore, were not included in the Updated GREET. GHG emissions are likely higher due to differing grid mix and electricity generation assumptions. The Industry and Updated total energy values are much higher than the previous GREET results due to the burden of transportation/production of ancillary materials for nickel production being included in the Nickel Institute LCI.

[17] See footnote 4 on page 12

2.1.4 Copper

2.1.4.1 Description of Process Stages

- Mining –Copper ores, mainly sulfide ores, are mining from both underground mines and open pit mines.
- Beneficiation – Ore is ground, then gravity, flotation, and organic chemicals are used to concentrate the copper to ~25%.
- There are two dominant methods for refining copper:
    - Pyrometallurgical Processing
        - Pre-treatment – Drying and roasting of copper to remove water (SO2 also removed)
        - Smelting/Reduction – copper is reduced using siliceous mixture
        - Refining – Electrolysis used to refine copper into copper cathode, which is then re-melted and cast before undergoing transformation processes
    - Hydrometallurgical Processing (This method is not considered in this project)
        - Pre-treatment – grinding or roasting of ore
        - Leaching – likely dump or heap leaching, sulfuric acid or ammonia-based solution applied to ore, soluble copper released from the ore
        - Electrowinning – electrolysis to separate copper from solution

2.1.4.2 Data Sources

Fthenakis et al. conducted a LCI for metals used in the production of photovoltaics[18]. Copper was included among these metals. The article and supporting report[19] aim to represent production in US and Canada.

Data Quality

Energy data was derived using published values from several copper producers. The distribution of energy among different fuels types was calculated using the fossil fuel distribution from the Manufacturing Energy Consumption Survey[20] for nonferrous metal production (excluding aluminum production). The non-combustion emissions reported were derived from Toxics Release Inventory data for Kennecott Utah Copper. In terms of sulfur capture, the authors acknowledge this operation has "one of cleanest copper smelters in the world". Therefore, sulfur emissions data was deemed to be unrepresentative of the North American copper industry as a whole and additional data contained within the article was used to calculate a SOx emissions value.

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[18] Fthenakis, V., Wang, W., & Kim, H. C., 2009. Life cycle inventory analysis of the production of metals used in photovoltaics. Renewable and Sustainable Energy Reviews, 13(3), 493-517.

[19] Fthenakis, V., Wang, W., & Kim, H. C., 2007. *Life cycle inventory analysis of the production of metals used in photovoltaics*. Brookhaven National Laboratory, BNL-77919-2007.

[20] Manufacturing energy consumption survey, 2002. *Table 1.2 First Use of Energy for All Purposes (Fuel and Nonfuel), 2002.* Energy Information Administration.

2.1.4.3 Other Data Sources

International Copper Association (ICA) – Cradle-to-gate life cycle inventory for copper production in the U.S. and Europe. Scott Baker, Director of the Environment Program at ICA, indicated that this study is currently in the process of peer review. It was not released in time for inclusion in this report, but this has the potential to be a valuable resource for future versions of GREET.

Chilean Copper Commission – Chile accounts for about one third of worldwide primary copper production. The Chilean Copper Commission has kept track of energy and emissions from the copper industry for the past decade. Yearly data is available on their website.

Metalytics – Using IEA data, a Northgate paper from CSIRO in Australia, and proprietary data, Metalytics has compiled energy consumption and GHG emissions data for aluminum, copper, and nickel. The energy data is broken down by process stage, but not by fuel type. The data was presented at the Joint ILZSG –ICSG –INSG Energy and Climate Change Policy Seminar in April 2009 in Lisbon, Portugal.

2.1.4.4 Data Preparation for GREET

1. **Energy values converted:** Energy data (allocated on a mass basis) were converted into the appropriate energy units.
2. **Particulate emissions:** The particulate emissions reported were assumed to be PM_{10}. $PM_{2.5}$ was assumed to be half of PM_{10} emissions.
3. **Sulfur oxide emissions:** As previously discussed, the SO_x emissions data was deemed to represent advanced copper processing and not the industry as a whole. In order to get a value that was more representative of the North American copper industry, a weighted average SOx emission factor (125,927 g/ton of Cu) of all the NA copper smelters referenced in the article was calculated.

2.1.4.5 Transformation Processes

It is assumed that copper being used in the automobile is largely copper wire. It is also assumed that 1 kg primary copper forms 1 kg of copper wire. Copper wire transformation data is sourced from the Sullivan, Burnham, and Wang report[21] produced in September 2010. Purchased energy units are converted into mmBtu/ton and input into the GREET model as a separate unit process stage.

[21] Sullivan, J. L., Burnham, A., and Wang, M. (2010) Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing. Argonne National Laboratory.

2.1.4.6 Total Energy and Emissions Results[22]

Table 2.14 shows total energy and emissions results using updated values.

Table 2.14: Total Energy and Emissions Results for Primary Copper (per ton of wire)

	Updated Values	GREET 2.7 in GREET
Energy Use (mmBtu/ton)		
Total Energy	43.299	95.706
Fossil fuels	43.299	90.137
Coal	3.334	26.203
Natural gas	36.309	37.620
Petroleum	3.656	26.314
Total Emissions(g/ton)	per ton	
VOC	475.308	666.630
CO	2010.997	2144.665
NOx	4156.742	9624.947
PM10	1174.039	7493.291
PM2.5	532.643	2860.383
SOx	127210.089	195054.269
CH4	6942.755	12162.939
N2O	57.020	88.318
CO2	2,838,004	7,355,950
CO2 (VOC, CO, CO2)	2,840,283	7,361,398
GHGs	3,030,844	7,691,790

The decrease in copper energy intensity compared to GREET 2.7 more likely a reflection of the variability in copper energy data and modeling rather than significant improvements in the production of copper. Fthenakis et al. review other energy data for the production of copper and found values ranging from 21.8 GJ/mton (21.9 mmBtu/ton) to 164.2 GJ/mton (171.5 mmBtu/ton). It is likely this project's results underestimate the energy intensity of copper production. The mining energy is based on a 3% ore concentration, which requires significantly less electricity to process than the lower grade ores that are typically extracted. In addition, only pyrometallurgical processing, which has a lower energy demand compared to hydrometallurgical processing, were considered.

[22] See footnote 4 on page 12

2.2 Plastics

2.2.1 High-Density Polyethylene (HDPE) Resin Production

2.2.1.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (ethylene) from processed natural gas and refined oil.
- Production of HDPE resin from ethylene.

2.2.1.2 Data Source(s)

The Plastics Division of the American Chemistry Council (ACC) (formerly American Plastics Council) was determined to have the best available life cycle inventory data for North American production of HDPE resin. Franklin Associates completed a report, *Cradle-To-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*, in February 2011 for ACC that, along with accompanying appendices, documents energy requirements and emissions for the production of HDPE resin.[23,24]

Primary data for ethylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for HDPE production were gathered from five plants in the U.S. and Canada for production year 2003.

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope, a trade association of plastic manufacturers with representation in 31 European countries, also has LCI data for HDPE resin production.[25] This is a good alternative data source, where, as of February 2011, the total energy result for HDPE resin differed by 8% from ACC value. However, the geographic scope of this dataset is not North American.

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[23] American Chemistry Council (ACC), Plastics Division (2011) *Final Report: Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*. Based on reports by Franklin Associates. http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only

[24] American Chemistry Council (ACC), Plastics Division (2011) *Final Appendices:Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*. Based on reports by Franklin Associates. http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-APPS-Only

[25] PlasticsEurope (2010) *The Plastics Portal: Eco-profiles*. http://www.plasticseurope.org/plastics-sustainability/eco-profiles.aspx

2.2.1.3 Data Preparation for GREET

The following steps were used to prepare data from the ACC report for insertion into the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. Fossil fuels that were used for feedstock sources or transportation were presented separately. The following fuel categorizes were used:
    - Residual oil
    - Diesel (included distillate oil)
    - Natural gas (NG)
    - Coal
    - Electricity
    - LPG
    - Gasoline
    - Internal offgas from NG
    - Internal offgas from oil
    - Oil as feed
    - NG as feed
   - Physical units of purchased energy for feedstock, process, and transportation energy were drawn from Table B-1 of the ACC report appendices.
   - Data were manipulated to convert reference flow from 1000 lbs resin to 2000 lbs (1 ton) resin.
   - Energy values were converted from physical units to mmBtu/ton resin using LHV factors found in GREET 1.8.c.
   - Internal offgas[26] energy values were drawn from the "Total Energy" column from appendices Table B-1, then manipulated to convert reference flow from 1000 lbs to 1 ton resin.
   - Recovered Energy values were determined in the same manner as internal offgas.
   - Recovered energy was excluded from the total as it was not possible to model in GREET using the data currently available, and it comprises only 1-2% of total "energy use."

2. **Add Non-combustion emissions:** The data presented in the ACC report separated emissions into combustion and process (non-combustion) emissions. Non-combustion emissions were reported in GREET.
   - Data for non-combustion emissions were taken from the "process emissions" column from Table 2-4 from the ACC report and converted to grams per ton of resin.

3. **Alterations to GREET model:** The previous GREET model was altered as follows:
   - LPG; gasoline; and internal offgas from oil and NG fuel categories were added.
   - A column to report feedstock energy separately in GREET was added.
   - Combustion of natural gas, petroleum, and internal offgas in the hydrocracker for olefin production creates an emissions profile different from standard combustion of natural gas and petroleum in an industrial boiler. To correctly account for these emissions, emissions factors (in g/mmBtu of natural gas) unique to each olefin must be multiplied by the amount

[26] Internal offgas results from the combustion of petroleum and natural gas feedstock in the hydrocracker. The energy from combustion is used in the production process and must be accounted for in process energy.

(in mmBtu) of natural gas combusted for each olefin needed to produce a particular resin. Hydrocracker emissions for ethylene, propylene, pyrolysis gas, and butadiene were provided by Franklin Associates and are available in the U.S. LCI Database (see Appendix). The following steps were taken so that the GREET model would accurately reflect emissions from the olefin production stage.
   - Emission factors from the hydrocracker for each olefin were added to GREET.
   - The portion of natural gas combusted for the plastic resin during the production of each olefin was calculated using weights of material inputs provided in the ACC report appendices for each unit process. For HDPE, 4.422 mmBtu of natural gas was combusted per ton of resin for production of ethylene.
   - In the calculations of total emissions, total mmBtu of natural gas used for olefin production was subtracted from the amount of natural gas combusted in an industrial boiler in order to avoid double counting of emissions (4.422 mmBtu for HDPE). The amount of natural gas used for each olefin was multiplied by the olefin's respective emissions profile.

4. **Transportation energy:** GREET does not currently include transportation of plastic resins in its model. Transportation data was compiled for possible future use by ANL. (See Appendix)
   - Transportation data were reported in both purchased energy and mmBtu per ton of resin.
   - Transportation energy requirements were also reported in terms of mode of transport and ton-miles per ton of resin.

2.2.1.4 Total Energy and Emissions Results[27]

Table 2.15 shows total energy and emissions results for HDPE resin production using updated values. Also presented are total energy and emissions results previously in GREET and from the ACC report. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results. The large increase in updated total energy over the total energy value previously in GREET could be due to inclusion of feedstock energy in the updated values.

[27] See footnote 4 on page 12

Table 2.15: Comparison of HDPE Resin Data

	Updated Values	GREET 2.7	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)			
Total Energy	63.688	45.977	*70.46
Fossil fuels	63.303	43.646	
Coal	1.803	10.994	
Natural gas	52.263	18.320	
Petroleum	9.237	14.332	
Total Emissions(g/ton)			
VOC	762.237	499.746	1069.242
CO	2970.417	1035.969	4596.638
NOx	1001.694	4725.855	2590.432
PM10	496.474	2622.888	242.508
PM2.5	128.645	965.636	13.228
SOx	21894.170	6344.230	26124.778
CH4	15043.573	5853.654	19510.910
N2O	15.197	41.271	19.842
CO2	1,289,195	3,521,214	1,511,114
CO2 (VOC, CO, CO2)	1,296,238	3,522,388	1,521,801
GHGs	1,676,856	3,681,028	1,999,593

*ACC energy values are reported in HHV.

2.2.2 Low-Density Polyethylene (LDPE) Resin Production

2.2.2.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (ethylene) from processed natural gas and refined oil.
- Production of LDPE resin from ethylene.

2.2.2.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of LDPE resin.

Primary data for ethylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for LDPE production were gathered from seven plants in the U.S. and Canada for production years 2002-2003.

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for LDPE resin differed by 12% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.2.3 Data Preparation for GREET

Data preparation for LDPE resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table C-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 3-4 of the ACC report. For step 3, calculations for LDPE resin production showed that 4.502 mmBtu of natural gas was combusted for ethylene production.

2.2.2.4 Total Energy and Emissions Results[28]

Table 2.16 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from the ACC report. LDPE was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.16: Comparison of LDPE Resin Data

	Updated Values	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)		
Total Energy	68.309	*75.064
Fossil fuels	67.908	
Coal	1.877	
Natural gas	56.795	
Petroleum	9.237	
Total Emissions(g/ton)		
VOC	806.224	1091.288
CO	3055.837	4464.361
NOx	1244.186	2590.432
PM10	506.331	231.485
PM2.5	134.102	6.063
SOx	22375.847	26565.703
CH4	15913.840	20062.066
N2O	20.406	22.046
CO2	1,526,400	1,564,224
CO2 (VOC, CO, CO2)	1,533,715	1,574,769
GHGs	1,937,642	2,067,936

*ACC energy values are reported in HHV.

2.2.3 Linear Low-Density Polyethylene (LLDPE) Resin Production

2.2.3.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (ethylene) from processed natural gas and refined oil.
- Production of LLDPE resin from ethylene.

2.2.3.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of LLDPE resin.

Primary data for ethylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for LLDPE production were gathered from seven plants in the U.S. and Canada for production year 2003.

[28] See footnote 4 on page 12

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for LLDPE resin differed by 13% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.3.3 Data Preparation for GREET

Data preparation for LLDPE resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table D-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 4-4 of the ACC report. For step 3, calculations for LLDPE resin production showed that 4.462 mmBtu of natural gas was combusted for ethylene production.

2.2.3.4 Total Energy and Emissions Results[29]

Table 2.17 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from the ACC report. LLDPE was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.17: Comparison of LLDPE Resin Data

	Updated Values	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)		
Total Energy	63.500	*70.256
Fossil fuels	63.169	
Coal	1.547	
Natural gas	52.433	
Petroleum	9.190	
Total Emissions(g/ton)		
VOC	767.095	1080.265
CO	3014.566	4519.476
NOx	1771.366	2480.200
PM10	426.794	209.439
PM2.5	111.877	11.023
SOx	22381.806	26345.240
CH4	15055.686	19731.372
N2O	30.070	38.581
CO2	2,395,936	1,541,263
CO2 (VOC, CO, CO2)	2,403,064	1,551,861
GHGs	2,788,417	2,040,378

*ACC energy values are reported in HHV.

[29] See footnote 4 on page 12

2.2.4 Polypropylene (PP) Resin Production

2.2.4.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (propylene) from processed natural gas and refined oil.
- Production of PP resin from propylene.

2.2.4.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of PP resin.

Primary data for propylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for PP production were gathered from four plants in the U.S. for production years 2003-2004.

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for PP resin differed by 13% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.4.3 Data Preparation for GREET

Data preparation for PP resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table E-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 5-4 of the ACC report. For step 3, calculations for PP resin production showed that 3.444 mmBtu of natural gas was combusted for propylene production.

2.2.4.4 Total Energy and Emissions Results[30]

Table 2.18 shows total energy and emissions results for PP resin production using updated values. Also presented are total energy and emissions results previously in GREET and from the ACC report. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results. The large increase in updated total energy over the total energy value previously in GREET is likely due to inclusion of feedstock energy in the updated values.

[30] See footnote 4 on page 12

Table 2.18: Comparison of PP Resin Data

	Updated Values	GREET 2.7	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)			
Total Energy	62.628	42.063	*68.676
Fossil fuels	62.204	39.468	
Coal	1.990	12.204	
Natural gas	41.972	15.724	
Petroleum	18.242	11.541	
Total Emissions(g/ton)			
VOC	627.027	475.145	892.872
CO	5759.420	940.900	7804.364
NOx	1358.622	4240.351	3130.564
PM10	496.921	2702.166	209.439
PM2.5	127.778	930.593	0.011
SOx	18477.988	6102.322	21935.995
CH4	13044.833	5271.525	17085.825
N2O	16.624	38.835	24.251
CO2	1,272,575	3,256,624	1,551,316
CO2 (VOC, CO, CO2)	1,283,580	3,257,690	1,566,556
GHGs	1,614,654	3,401,051	1,980,853

*ACC energy values are reported in HHV.

2.2.5 Polyethylene Terephthalate (PET) Resin Production

2.2.5.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (ethylene), paraxylenes, carbon monoxide, and methanol from processed natural gas and refined oil.
- Manufacture of ethylene oxide from oxygen and ethylene.
- Manufacture of ethylene glycol from ethylene oxide.
- Manufacture of acetic acid from methanol and carbon monoxide.
- Manufacture of terephthalic acid (TPA) from paraxylene and acetic acid.
- Manufacture of purified terephthalic acid (PTA) from TPA
- Manufacture of dimethyl terephthalate (DMT) from TPA and methanol.
- Production of PET resin from ethylene glycol and DMT or PTA.

2.2.5.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of PET resin.

Primary data for ethylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for acetic acid production were gathered from two plants in the U.S. for production years 1994 and 2003. Primary data for oxygen manufacture were gathered from three producers in the North America for production years 1990-1993. Primary data for ethylene oxide manufacture were gathered from six producers in the U.S. and Europe for production years 1990-1992. Primary data for TPA and PTA and PET production from PTA were gathered from two plants in the U.S. for production years 2001 and 2003-2004. Primary data for DMT and PET production from DMT were gathered in North America in the early 1990's.

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for PET resin differed by 4% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.5.3 Data Preparation for GREET

Data preparation for PET resin production followed the same procedure as for HDPE resin production (section 0) with the exception that energy use data were taken from Table F-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 6-4 of the ACC report. For step 3, calculations for PET resin production showed that 0.768 mmBtu of natural gas was combusted for ethylene production.

2.2.5.4 Total Energy and Emissions Results[31]

Table 2.19 shows total energy and emissions results for PET resin production using updated values. Also presented are total energy and emissions results previously in GREET and from the ACC report. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results. The large decrease in updated total energy over the total energy value previously in GREET could be due to the reduction of input materials to the final production stage. The ACC data show that PET resin production used less than one half the amount of ethylene glycol and two-thirds the amount of xylenes shown in the report used for previous GREET values.

[31] See footnote 4 on page 12

Table 2.19: Comparison of PET Resin Data

	Updated Values	GREET 2.7	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)			
Total Energy	55.563	74.537	*60.814
Fossil fuels	54.601	72.927	
Coal	5.225	7.892	
Natural gas	24.223	16.531	
Petroleum	25.153	48.503	
Total Emissions(g/ton)			
VOC	334.495	676.980	639.341
CO	12667.965	1730.703	18077.905
NOx	2367.272	9429.901	6657.960
PM10	1192.370	3585.871	319.670
PM2.5	404.794	1804.166	0.000
SOx	8673.291	12421.151	9060.999
CH4	9264.640	8101.291	13778.891
N2O	28.895	49.668	52.911
CO2	2,053,513	6,011,201	2,586,243
CO2 (VOC, CO, CO2)	2,074,463	6,013,162	2,617,046
GHGs	2,314,689	6,230,495	2,932,148

*ACC energy values are reported in HHV.

2.2.6 General Purpose Polystyrene (GPPS) Resin Production

2.2.6.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (ethylene and pyrolysis gas) and naphtha from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of styrene from benzene and ethylene.
- Production of GPPS resin from styrene.

2.2.6.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of GPPS resin.

Primary data for ethylene and pyrolysis gas production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for benzene production were gathered from one plant in the U.S. for production year 2003. Two other datasets for North American benzene production were collected in 1992. Primary data for ethylbenzene and styrene production were gathered from two plants in the U.S. for production years 2002-2003. A third dataset for North American ethylbenzene and styrene production was collected in 1993. Primary data for GPPS production were gathered from six plants in the U.S. for production years 2000-2003.

<u>Data Quality</u>

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for GPPS resin differed by 13% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.6.3 Data Preparation for GREET

Data preparation for GPPS resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table G-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 7-4 of the ACC report. For step 3, calculations for GPPS resin production showed that a total of 2.258 mmBtu of natural gas was combusted for olefin production, 1.307 mmBtu for ethylene and 0.951 mmBtu for pyrolysis gas.

2.2.6.4 Total Energy and Emissions Results[32]

Table 2.20 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from the ACC report. GPPS was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.20: Comparison of GPPS Resin Data

	Updated Values	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)		
Total Energy	76.221	*82.668
Fossil fuels	75.659	
Coal	2.640	
Natural gas	42.665	
Petroleum	30.354	
Total Emissions(g/ton)		
VOC	534.047	1058.219
CO	9737.139	14219.816
NOx	2598.084	6514.660
PM10	672.173	286.601
PM2.5	246.378	8.598
SOx	13718.710	16093.745
CH4	13014.442	19290.448
N2O	28.755	41.888
CO2	2,288,062	2,993,878
CO2 (VOC, CO, CO2)	2,305,028	3,019,855
GHGs	2,638,958	3,494,327

*ACC energy values are reported in HHV.

[32] See footnote 4 on page 12

2.2.7 High-Impact Polystyrene (HIPS) Resin Production

2.2.7.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (ethylene, pyrolysis gas, and butadiene) and naphtha from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of styrene from benzene and ethylene.
- Manufacture of polybutadiene from butadiene.
- Production of HIPS resin from styrene, polybutadiene, and mineral oil.

2.2.7.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of HIPS resin.

Primary data for ethylene and pyrolysis gas production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for butadiene production were gathered from three thermal-cracking units in the U.S. and Canada for production year 2003. Primary and secondary production data for polybutadiene production were collected in the 1970's. Primary data for benzene production were gathered from one plant in the U.S. for production year 2003. Two other datasets for North American benzene production were collected in 1992. Primary data for ethylbenzene and styrene production were gathered from two plants in the U.S. for production years 2002-2003. A third dataset for North American ethylbenzene and styrene production was collected in 1993. Primary data for HIPS production were gathered from six plants in the U.S. for production years 2000-2003.

<u>Data Quality</u>

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

<u>Other Data Sources</u>

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for HIPS resin differed by 13% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.7.3 Data Preparation for GREET

Data preparation for HIPS resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table H-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 8-4 of the ACC report. For step 3, calculations for HIPS resin production showed that a total of 2.125 mmBtu of natural gas was combusted for olefin production, 1.225 mmBtu for ethylene, 0.155 mmBtu for butadiene, and 0.745 mmBtu for pyrolysis gas.

2.2.7.4 Total Energy and Emissions Results[33]

Table 2.21 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from the ACC report. HIPS was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.21: Comparison of HIPS Resin Data

	Updated Values	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)		
Total Energy	76.892	*83.44
Fossil fuels	76.321	
Coal	2.683	
Natural gas	43.271	
Petroleum	30.368	
Total Emissions(g/ton)		
VOC	549.841	1069.242
CO	9669.043	14219.816
NOx	2578.898	6602.845
PM10	683.432	297.624
PM2.5	243.984	8.047
SOx	14200.043	16644.901
CH4	13223.193	19510.910
N2O	28.044	41.888
CO2	2,277,184	3,013,146
CO2 (VOC, CO, CO2)	2,294,091	3,039,158
GHGs	2,633,028	3,508,657

*ACC energy values are reported in HHV.

2.2.8 Polyvinyl Chloride (PVC) Resin Production

2.2.8.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (ethylene) from processed natural gas and refined oil.
- Mining of salt (NaCl) and production of chlorine.
- Production of hydrogen to manufacture hydrochloric acid from hydrogen and chlorine.
- Manufacture of vinyl chloride monomer (VCM) from ethylene, chlorine, and hydrochloric acid.
- Production of PVC resin from VCM.

2.2.8.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of PVC resin.

Primary data for ethylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. PlasticsEurope provided the data for mining of NaCl. Primary data for chlorine production were gathered from three plants in the U.S. for production year 2003. Four other datasets for North American chlorine production were collected in 1989-1992. Data for production of HCl is from the Swiss Center for LCI's Ecoinvent Database[34] and represents European production for the

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[33] See footnote 4 on page 12

[34] Swiss Centre for Life Cycle Inventories (2011) http://www.ecoinvent.ch/

years 1997-2000. Primary data for VCM and PVC production were gathered from three plants in the U.S. for production years 2003-2004.

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for HIPS resin differed by 7% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.8.3 Data Preparation for GREET

Data preparation for PVC resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table I-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 9-4 of the ACC report. For step 3, calculations for PVC resin production showed that 2.025 mmBtu of natural gas was combusted for ethylene production.

2.2.8.4 Total Energy and Emissions Results[35]

Table 2.22 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from the ACC report. PVC was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

[35] See footnote 4 on page 12

Table 2.22: Comparison of PVC Resin Data

	Updated Values	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)		
Total Energy	46.769	*51.838
Fossil fuels	45.858	
Coal	4.697	
Natural gas	36.663	
Petroleum	4.498	
Total Emissions(g/ton)		
VOC	477.579	738.549
CO	1729.824	3020.333
NOx	1883.981	3626.604
PM10	984.973	253.532
PM2.5	291.827	1.213
SOx	11382.554	12345.887
CH4	9717.414	13558.429
N2O	26.551	42.990
CO2	1,828,459	2,013,151
CO2 (VOC, CO, CO2)	1,832,665	2,020,286
GHGs	2,083,513	2,354,537

*ACC energy values are reported in HHV.

2.2.9 Acrylonitrile-Butadiene-Styrene (ABS) Resin Production

2.2.9.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (ethylene, pyrolysis gas, butadiene, and propylene), naphtha, and ammonia from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of styrene from benzene and ethylene.
- Manufacture of acrylonitrile from polypropylene and ammonia.
- Manufacture of polybutadiene from butadiene.
- Production of ABS resin from polybutadiene, acrylonitrile, and styrene.

2.2.9.2 Data Source(s)

The ACC was determined to have the best available life cycle inventory data for North American production of ABS resin.

Primary data for ethylene and pyrolysis gas production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for butadiene production were gathered from three thermal-cracking units in the U.S. and Canada for production year 2003. Primary and secondary production data for polybutadiene production were collected in the 1970's. Primary data for benzene production were gathered from one plant in the U.S. for production year 2003. Two other datasets for North American benzene production were collected in 1992. Primary data for ethylbenzene and styrene production were gathered from two plants in the U.S. for production years 2002-2003. A third dataset for North American ethylbenzene and styrene production was collected in 1993. Primary data for ABS production were gathered from five plants in the U.S. and Mexico for production years 2003-2004.

Data Quality

These data were compiled by Franklin Associates, a well-respected life cycle practitioner, and as such, the results were deemed to be of high quality. Total non-combustion emissions from the ACC report included emissions due to upstream fuel production for transportation. Although transportation energy was not included in the final results of this GREET update report, the non-combustion emissions from transportation were not removed. As energy for transportation is minimal, it is likely that non-combustion emissions from fuel production for transportation would be quite small and have little effect on total emissions.

Other Data Sources

PlasticsEurope provides a good alternative data source, where, as of February 2011, the total energy result for ABS resin differed by 13% from ACC value. However, the geographic scope of this dataset is not North American.

2.2.9.3 Data Preparation for GREET

Data preparation for ABS resin production followed the same procedure as for HDPE resin (section 0) with the exception that energy use data were taken from Table J-1 of the ACC report appendices and non-combustion emissions data were drawn from Table 10-4 of the ACC report. For step 3, calculations for ABS resin production showed that a total of 2.125 mmBtu of natural gas was combusted for olefin production, 0.879 mmBtu for ethylene, 0.588 mmBtu for propylene, 0.348 mmBtu for butadiene, and 0.535 mmBtu for pyrolysis gas.

2.2.9.4 Total Energy and Emissions Results[36]

Table 2.23 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from the ACC report. ABS was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the ACC reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

[36] See footnote 4 on page 12

Table 2.23: Comparison of ABS Resin Data

	Updated Values	Industry Source Plastics Div, ACC
Energy Use (mmBtu/ton)		
Total Energy	83.801	*91.44
Fossil fuels	82.592	
Coal	6.997	
Natural gas	48.467	
Petroleum	27.128	
Total Emissions(g/ton)		
VOC	676.452	1157.427
CO	9196.307	13558.429
NOx	3586.311	8465.751
PM10	1560.829	485.017
PM2.5	489.655	5.842
SOx	17957.286	19621.141
CH4	14962.518	21935.995
N2O	33.223	78.264
CO2	2,753,184	3,550,765
CO2 (VOC, CO, CO2)	2,769,744	3,576,002
GHGs	3,153,707	4,107,212

*ACC energy values are reported in HHV.

2.2.10 Ethylene Propylene Diene Monomer (EPDM) Resin Production

2.2.10.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (ethylene, propylene, and butadiene) and naphtha from processed natural gas and refined oil.
- Manufacture of cyclopentadiene from steam cracking of naphtha.[37]
- Manufacture of ethylidene norbornene from cyclopentadiene and butadiene.[38]
- Production of EPDM resin from ethylene, propylene and ethylidene norbornene.

2.2.10.2 Data Source(s)

No recent, publicly available source was found for EPDM. In a report for the Athena Sustainable Material Institute, Franklin Associates modeled the production of EPDM assuming that the composition of EPDM resin was approximately 65% ethylene, 31% propylene, and 4% diene.[39] This assumption was based on a conversation with UniRoyal Chemical, a former leading manufacturer of EPDM. Franklin Associates could not find a data source for production of ethylidene norbornene, the preferred diene for EPDM, and consequently used butadiene production as a substitute. For this study, the model of EPDM resin

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[37] Hönicke, D., Födisch, R., Claus, P. and Olson, M. (2000) Cyclopentadiene and Cyclopentene. Ullmann's Encyclopedia of Industrial Chemistry. http://onlinelibrary.wiley.com/doi/10.1002/14356007.a08_227/full

[38] Kent and Riegel's Handbook of Industrial Chemistry and Biotechnology, 11th Edition (2007) Edited by James A. Kent. pp. 706. http://books.google.com/books?id=AYjFoLCNHYUC&pg=PA706&lpg=PA706&dq=%22ethylidene+norbornene%22+and+butadiene+and+cyclopentadiene&source=bl&ots=GPUxMw4sEE&sig=jeoIIEHiWQ50iT2lqO0f6QuIgsQ&hl=en&ei=ahxyTqDyDITz0gHr5fGkCg&sa=X&oi=book_result&ct=result&resnum=6&ved=0CEAQ6AEwBQ#v=onepage&q&f=false

[39] Athena Sustainable Materials Institute (2001) Life Cycle Inventory of Selected Commercial Roofing Products. Based on reports by Franklin Associates.

production used the material composition suggested in the 2001 Athena report, but was built using unit processes from the 2011 ACC plastics report.

Primary data for ethylene and propylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for butadiene production were gathered from three thermal-cracking units in the U.S. and Canada for production year 2003.

Data Quality

As production of ethylidene norbornene requires other chemical inputs and several production steps beyond butadiene manufacture, this model of EPDM resin is expected to have lower than actual energy and emissions results.

2.2.10.3 Data Preparation for GREET

The following steps were used to model EPDM resin production and prepare the results for insertion into the GREET model.

1. **Model energy use and emissions for EPDM resin production:** Unit processes for extraction of crude oil, refining of petroleum products, extraction of natural gas, processing of natural gas, production of ethylene, production of propylene, and production of butadiene were weighted and combined to model EPDM resin production.
   - Physical units of purchased energy for feedstock, process, and transportation energy as well as atmospheric non-combustion emissions were drawn from Tables B-2, B-3, B-4, B-5, B-6, E-2, and H-2 of the ACC report appendices.
   - Weights of material inputs for each unit process provided in the ACC report appendices were used to determine the amount of fuel use, transportation, and emissions resulting from the manufacture of 653.125 lbs of ethylene, 307.8125 lbs of propylene, and 39.0625 lbs of butadiene. These factors were derived from the Athena roofing study where Franklin Associates assumed that 640 lbs of EPDM resin was composed of 418 lbs ethylene, 197 lbs propylene, and 25 lbs butadiene.
   - The resulting datasets for ethylene, propylene, and butadiene were summed to make one data set for 1000 lbs of EPDM resin.
2. **Add fuel energy, non-combustion emissions, and modification of GREET:** From this point, data processing matched steps 1-4 for HDPE resin (section 0) with the following exceptions.
   - The dataset from step 1 above was used for feedstock, process energy, emissions, and transportation.
   - For step 3, calculations for EPDM resin production showed that a total of 4.075 mmBtu of natural gas was combusted for olefin production, 2.917 mmBtu for ethylene, 1.064 mmBtu for propylene, and 0.093 mmBtu for butadiene.

2.2.10.4 Total Energy and Emissions Results[40]

Table 2.24 shows total energy and emissions results using updated values. EPDM data were not previously included in GREET or published in full by an industry or in literature, so no comparison is possible between updated and previous GREET or industry results.

[40] See footnote 4 on page 12

Table 2.24: EPDM Resin Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	67.918
Fossil fuels	67.699
Coal	1.027
Natural gas	52.655
Petroleum	14.017
Total Emissions(g/ton)	
VOC	693.878
CO	3709.203
NOx	763.261
PM10	306.210
PM2.5	67.445
SOx	20605.933
CH4	13776.766
N2O	9.880
CO2	1,011,176
CO2 (VOC, CO, CO2)	1,019,167
GHGs	1,366,531

2.2.11 Nylon 66 Resin Production

2.2.11.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (ethylene, pyrolysis gas, butadiene, and propylene), naphtha, and ammonia from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of adipic acid from benzene and nitric acid.
- Manufacture of acrylonitrile from polypropylene and ammonia.
- Manufacture of hexamethylene diamine from acrylonitrile or butadiene.
- Production of nylon 66 from adipic acid and hexamethyl diamine.

2.2.11.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for production of nylon 66 resin. No other publicly available source of nylon 66 production data provides the level of detail necessary for use in the GREET model. All PlasticsEurope eco-profiles were found on their website.

Primary data for ethylene, pyrolysis gas, and propylene production were gathered from 17 European manufacturing sites for production year 1999. Primary data for butadiene production were gathered from three European manufacturing sites for production year 1997. Primary data for benzene production were gathered from eleven European manufacturing sites for production year 2002. Primary data for ammonia production were gathered from one European manufacturing site for production year 2001. Primary data for acrylonitrile production were gathered from three European manufacturing sites for production year 1995. Primary data for nylon 66 production were gathered from four European manufacturing sites for production year 1996.

<u>Data Quality</u>

These data were compiled by well-respected life cycle practitioners employed by PlasticsEurope, who work with more than 100 polymer manufacturers, which represents over 90% of European plastics production, and as such, the results were deemed to be of high quality.

2.2.11.3 Data Preparation for GREET

The following steps were used to prepare data for nylon 66 from PlasticsEurope for use in the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. Fossil fuels that were used for feedstock sources or transportation were presented separately. The following fuel categorizes were used:
    - o Crude oil
    - o Natural gas (NG)
    - o Coal
    - o Electricity
    - o Oil as feed
    - o NG as feed
    - Purchased energy for feedstock and process energy ("energy content of delivered fuel") were taken from Table 2 of the nylon 66 eco-profile. "Oil fuels" were assumed to be crude oil, and "other fuels" were assumed to be natural gas.
    - Purchased energy for transportation was also derived from Table 2, but had to be estimated due to the upstream energy included in the "energy use in transport" category. The "energy use in transport" value for each fuel category (electricity, oil fuels, and other fuels) was multiplied by the ratio of "energy content of delivered fuel" to "total energy" for the corresponding fuel category to estimate the amount of delivered, or purchased, energy was used in transportation.
    - Data were manipulated to convert reference flow from 1 kg of resin to 1 ton of resin.
    - Energy values were converted from HHV in MJ to physical U.S. customary units using HHV factors for each fuel found in GREET 1.8.c.
    - Conversion of energy values from physical units to mmBtu/ton resin using LHV factors found in GREET 1.8.c.

2. **Add Non-combustion emissions:** The data presented in the eco-profile separated emissions into several categories, including process (non-combustion) emissions. Non-combustion emissions were reported in GREET.
    - Data for non-combustion emissions were drawn from the "from process" column in Table 7 of the nylon 66 eco-profile and converted to grams per ton of resin.

3. **Alterations to GREET model:** The previous GREET model was altered as follows:
    - A crude oil fuel category was added.
    - A column to report feedstock energy separately in GREET was added.

4. **Transportation energy:** GREET does not currently include transportation of plastic resins in its model. Transportation data was compiled for possible future use by ANL. (See Appendix)
    - Transportation data were reported in both purchased energy and mmBtu per ton of resin.

2.2.11.4 Total Energy and Emissions Results[41]

Table 2.25 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from PlasticsEurope. Nylon 66 was not previously included in GREET, so no

[41] See footnote 4 on page 12

comparison is possible between updated and previous results. Note that the PlasticsEurope reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.25: Comparison of Nylon 66 Resin Data

	Updated Values	Industry Source PlasticsEurope
Energy Use (mmBtu/ton)		
Total Energy	105.129	*119.202
Fossil fuels	102.680	110.167
Coal	11.440	15.903
Natural gas	58.848	58.513
Petroleum	32.391	35.749
Total Emissions(g/ton)		
VOC	442.774	19.675
CO	3093.002	6637.763
NOx	8186.669	12280.543
PM10	2709.107	1931.106
PM2.5	880.287	
SOx	8869.070	16161.913
CH4	11554.776	44688.010
N2O	744.446	668.100
CO2	5,377,578	5,934,498
CO2 (VOC, CO, CO2)	5,383,818	5,945,131
GHGs	5,894,533	7,184,794

*PlasticsEurope energy values are reported in HHV.

2.2.12 Nylon 6 Resin Production

2.2.12.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefin (pyrolysis gas) and naphtha from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of cyclohexanone from benzene and phenol.
- Manufacture of caprolactam from cyclohexanone.
- Production of nylon 6 resin from caprolactam.

2.2.12.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for production of nylon 6 resin. No other publicly available source of nylon 6 production data provides the level of detail necessary for use in the GREET model.

Primary data for pyrolysis gas production were gathered from 17 European manufacturing sites for production year 1999. Primary data for benzene production were gathered from eleven European manufacturing sites for production year 2002. Primary data for phenol production were gathered from two European manufacturing sites for production year 1994.

2.2.12.3 Data Preparation for GREET

Data preparation for use in GREET for nylon 6 resin production was the same as for nylon 66 (section 2.2.11.3) except that energy data were taken from Table 1 and emissions data were from Table 6 of the nylon 6 eco-profile.

2.2.12.4 Total Energy and Emissions Results[42]

Table 2.26 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from PlasticsEurope. Nylon 6 was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the PlasticsEurope reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.26: Comparison of Nylon 6 Resin Data

	Updated Values	GREET 2.7	Industry Source PlasticsEurope
Energy Use (mmBtu/ton)			
Total Energy	92.208	–	*103.588
Fossil fuels	90.790	–	95.784
Coal	6.626	–	11.939
Natural gas	54.597	–	50.679
Petroleum	29.566	–	33.165
Total Emissions(g/ton)			
VOC	407.128	–	18.481
CO	6528.715	–	8836.469
NOx	14014.264	–	16866.847
PM10	1884.136	–	2640.409
PM2.5	712.631	–	
SOx	8489.632	–	15058.231
CH4	11448.642	–	42518.689
N2O	7890.922	–	7809.753
CO2	5,255,372	–	4,954,035
CO2 (VOC, CO, CO2)	5,266,901	–	4,968,166
GHGs	7,904,612	–	8,280,100

*PlasticsEurope energy values are reported in HHV.

2.2.13 Liquid Epoxy Resin Production

2.2.13.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (propylene, pyrolysis gas) and naphtha from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of epichlorohydrin from propylene and chlorine.
- Manufacture of Bisphenol-A from benzene, propylene, acetone, and phenol.
- Production of liquid epoxy resin from epichlorohydrin and bisphenol-A.

2.2.13.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for production of liquid epoxy resin. No other publicly available source of epoxy production data provides the level of detail necessary for use in the GREET model.

Primary data for propylene and pyrolysis gas production were gathered from 17 European manufacturing sites for production year 1999. Primary data for benzene production were gathered from eleven European manufacturing sites for production year 2002. Primary data for phenol production were gathered from two European manufacturing sites for production year 1994. Primary data for

[42] See footnote 4 on page 12

acetone production were gathered from two European manufacturing sites for production year 1994. Primary data for chlorine production were gathered from 97 European manufacturing sites for production year 1994.

2.2.13.3 Data Preparation for GREET

Data preparation for use in GREET for liquid epoxy resin production followed the same procedure as for nylon 66 (section 2.2.11.3) using the liquid epoxy eco-profile.

2.2.13.4 Total Energy and Emissions Results[43]

Table 2.27 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from PlasticsEurope. Liquid epoxy was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the PlasticsEurope reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.27: Comparison of Liquid Epoxy Resin Data

	Updated Values	Industry Source PlasticsEurope
Energy Use (mmBtu/ton)		
Total Energy	106.283	*117.885
Fossil fuels	103.974	106.534
Coal	10.787	10.653
Natural gas	70.596	70.292
Petroleum	22.591	25.585
Total Emissions(g/ton)		
VOC	487.823	7.777
CO	2042.538	4259.720
NOx	7638.815	12169.988
PM10	8529.681	7833.753
PM2.5	844.060	
SOx	8130.174	10805.578
CH4	12785.464	92198.337
N2O	88.696	0.003
CO2	5,222,053	5,178,627
CO2 (VOC, CO, CO2)	5,226,783	5,185,435
GHGs	5,572,851	7,317,902

*PlasticsEurope energy values are reported in HHV.

[43] See footnote 4 on page 12

2.2.14 Polycarbonate (PC) Resin Production

2.2.14.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Mining of salt (NaCl) and production of chlorine and sodium hydroxide.
- Manufacture of olefins (propylene, pyrolysis gas) and naphtha from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of Bisphenol-A from benzene, propylene, acetone, and phenol.
- Manufacture of phosgene from chlorine and sodium hydroxide.
- Production of liquid epoxy resin from bisphenol-A and phosgene.

2.2.14.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for production of PC resin. No other publicly available source of PC production data provides the level of detail necessary for use in the GREET model.

Primary data for propylene and pyrolysis gas production were gathered from 17 European manufacturing sites for production year 1999. Primary data for benzene production were gathered from eleven European manufacturing sites for production year 2002. Primary data for phenol production were gathered from two European manufacturing sites for production year 1994. Primary data for acetone production were gathered from two European manufacturing sites for production year 1994. Primary data for chlorine production were gathered from 97 European manufacturing sites for production year 1994. Primary data for polycarbonate production were gathered from five European manufacturing sites for production year 2007.

Data Quality

This PlasticsEurope eco-profile provided only total energy values including upstream energy. As such, an estimation of purchased energy using the GREET model was necessary. Since the removal of upstream energy required use of GREET assumptions based on fuel production and delivery in the U.S., which was not ideal given that European fuel production and delivery data was likely utilized in the PC eco-profile, this estimation introduced uncertainty and possibly significant error into the total energy and emissions results. Although this data source provided a list of total emissions, it was not possible to separate out non-combustion emissions for inclusion in the GREET model. Additionally, this data set did not include energy use or emissions from transportation as it was expected to be less than 2% of total energy use and therefore not significant. Lastly, the eco-profile authors noted uncertainty in how much feedstock was combusted in the hydrocracker and became a process fuel. If the amount of feedstock combusted was over-estimated, total emissions results would be too high, or too low if feedstock combustion was under-estimated.

2.2.14.3 Data Preparation for GREET

The following steps were used to prepare data for PC from PlasticsEurope for use in the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. Fossil fuels that were used for feedstock sources were presented separately. The following fuel categorizes were used:
    - Crude oil
    - Natural gas (NG)

- o Coal
- o Electricity
- o Oil as feed
- o NG as feed

- Feedstock energy and process energy, in primary energy form, were derived from Table 2 of the PC eco-profile. If presented with a range of values (a result of uncertainty in feedstock combustion) the median of the range was used. Feedstock values were taken directly from "Feedstock Energy Input." To calculate the amount of primary energy used for electricity, both "Fuel Energy Input" and "Feedstock Energy Input" categories were subtracted from the "Total Energy Input" category, and the results were summed. "Fuel Energy Input" was used to determine primary process energy. To simplify the modeling of fuel energy input, lignite was grouped with coal and fuel energy from nuclear, biomass, wood, and other renewables were disregarded as they represented less than 1 ten-thousandth of a percent of total fuel energy input.

2. **Excel Solver:** Solver was used to estimate purchased energy from the primary energy values.
   - The objective was set to equal the value of total energy of a selected fuel entered into the "Total Energy" cell in the GREET model. (See Input to Total Energy in Table 2.28.)
   - The "energy use" value for the selected fuel was the variable cell that Solver changed so that the "Total Energy" matched the input. The value returned by Solver in the "energy use" cell was used as the purchased energy value for that fuel. (See Output to Energy Use in Table 2.28.)
   - This process was repeated separately for each fuel type.

Table 2.28: Inputs to GREET and Outputs from Solver for PC Purchased Energy Calculation

Fuel Type	Input to Total Energy	Output to Energy Use
	(mmBtu/ton resin)	
Crude Oil	9.591	8.502
Natural Gas	29.961	27.930
Coal	0.408	0.400
Electricity	14.695	5.730

- Data were manipulated to convert reference flow from 1 kg of resin to 1 ton of resin.
- Energy values were converted from HHV in MJ to physical U.S. customary units using HHV factors for each fuel found in GREET 1.8.c.
- Conversion of energy values from physical units to mmBtu/ton resin using LHV factors found in GREET 1.8.c.

1. **Alterations to GREET model:** The previous GREET model was altered as follows:
   - A crude oil fuel category was added.
   - A column to report feedstock energy separately in GREET was added.

2.2.14.4 Total Energy and Emissions Results[44]

Table 2.29 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from PlasticsEurope. PC was not previously included in GREET, so no

[44] See footnote 4 on page 12

comparison is possible between updated and previous results. Note that the PlasticsEurope reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.29: Comparison of PC Resin Data

	Updated Values	Industry Source PlasticsEurope
Energy Use (mmBtu/ton)		
Total Energy	83.263	*89.935
Fossil fuels	81.245	83.349
Coal	9.827	5.890
Natural gas	37.761	38.351
Petroleum	33.658	36.451
Total Emissions(g/ton)		
VOC	355.523	2275.052
CO	1284.459	1451.496
NOx	5354.616	4508.708
PM10	2139.440	27.488
PM2.5	746.170	90.718
SOx	6676.477	3710.386
CH4	8003.297	10953.294
N2O	67.393	79.288
CO2	3,768,919	3,456,374
CO2 (VOC, CO, CO2)	3,772,046	3,465,848
GHGs	3,992,211	3,746,673

*PlasticsEurope energy values are reported in HHV.

2.2.15 Rigid Polyurethane (PUR) Foam Production

2.2.15.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Mining of salt (NaCl) and production of chlorine, NaOH, and potassium hydroxide (KOH).
- Manufacture of olefins (propylene, pyrolysis gas), ammonia, naphtha, and formaldehyde from processed natural gas and refined oil.
- Manufacture of benzene from pyrolysis gas and naphtha.
- Manufacture of aniline from ammonia and benzene.
- Manufacture of phosgene from chlorine and sodium hydroxide.
- Production of methylene diphenylene diisocyanate (MDI) from phosgene, formaldehyde, and aniline.
- Manufacture of sucrose from sugar beets.
- Manufacture of propylene oxide from propylene, chlorine, oxygen, NaCl, and NaOH.
- Production of polyol for rigid foam from propylene oxide, sucrose, KOH and limestone.
- Production of rigid polyurethane foam from polyol for rigid foam and MDI.

2.2.15.2 Data Source(s)

While the ACC report provides data concerning precursor resins for rigid polyurethane foam, it does not address the final production stage where the precursor polyol and isocyanate, MDI, are mixed to create the rigid PUR foam. PlasticsEurope has a module that accounts for all production stages for rigid PUR foam. However, in the 2011 ACC report, Franklin Associates noted that PlasticsEurope total energy values for MDI were quite high due to incorrect allocation to HCl production. Ideally, North American data would be used, but the final stage of production should also be included. Thus a model was created where European data for the final production stage was added to the North American data for the precursors.

Primary data for propylene and pyrolysis gas production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for oxygen manufacture were gathered from three producers in the North America for production years 1990-1993. PlasticsEurope provided the data for mining of NaCl. Primary data for chlorine production were gathered from three plants in the U.S. for production year 2003. Primary data for polyether polyol for rigid foam manufacture were gathered from three plants in the U.S. for production year 2003. Primary data for benzene production were gathered from one plant in the U.S. for production year 2003. Primary data for nitric acid fabrication were gathered from a European source in 1990. Primary data for nitrobenzene and aniline production were gathered from two plants in the U.S. for production years 2003-2004. Primary data for formaldehyde production were gathered from one producer in the U.S. for production year 2007. Primary data for MDI production were gathered from four plants in the U.S. for production year 2003. Primary data for rigid PUR foam production were gathered from one European site in 1996.

Data Quality

In order to get a dataset for final production stage energy and emissions due to precursor production had to be subtracted out using European data from PlasticsEurope eco-profiles for MDI and polyol. An assumption had to be made, based on the rigid PUR foam eco-profile, about how much MDI and polyol was used in the rigid foam production. If the weight factors used in the calculations were incorrect, or the division between precursor and foam production was not exact, errors in the total energy and emissions would result.

2.2.15.3 Data Preparation for GREET

The following steps were used to prepare data for PUR precursor production from the ACC report and rigid PUR foam production from PlasticsEurope eco-profiles for use in the GREET model.

1. **Preparation of North American precursor data:** Feedstock, process, and transportation energy values as well as non-combustion emissions for each precursor were weighted and added together.
    - Physical units of purchased energy for feedstock, process, and transportation energy were drawn from Table K-1 and M-1 of the ACC report appendices for rigid foam polyol and MDI, respectively.
    - Internal offgas and recovered energy values were also taken from the “Total Energy” column from appendices Table K-1 and M-1.
    - Energy data for each precursor were manipulated to convert reference flow from 1000 lbs resin to 2000 lbs (1 ton) resin.
    - Non-combustion emissions data were taken from the “process emissions” column from Table 11-4 and Table 13-4 from the ACC report for the polyol and MDI and converted to grams per ton of resin.
    - Both polyol and MDI datasets, including emissions, were multiplied by 0.5 (to model how much of each precursor is in a ton of rigid PUR foam) and then summed.

2. **Preparation of European final production stage data:** Feedstock, process, and transportation energy values as well as non-combustion emissions for each precursor were weighted and added together, then subtracted from the full rigid PUR foam dataset.
    - Energy use data preparation step 1, parts 1-4, for nylon 66 resin (section 2.2.11.3) was followed using PlasticsEurope data from Table 1 of the polyol and MDI eco-profiles and Table 3 of the rigid PUR foam production eco-profile.

- Non-combustion emissions data were drawn from the "from process" column in Table 6 of the polyol and MDI eco-profiles and Table 8 of the rigid PUR foam eco-profile and converted to grams per ton of resin.
- Datasets, including emissions, for the polyol and MDI were multiplied by 0.386 and 0.616, respectively, and subtracted from the rigid PUR foam dataset.

3. **Combination of the North American precursor and European final production stage data:** Data calculated for North American precursors and European final production stage were summed.
   - The North American precursor dataset resulting from step 1 above was added to the European dataset resulting from step 2 above.
   - Energy values were converted from physical units to mmBtu/ton resin using LHV factors found in GREET 1.8.c.
   - Recovered energy was excluded from the total as it was not possible to model in GREET using the data currently available, and it comprises only 1-2% of total "energy use."
   - Final data preparation was the same as step 3 for HDPE resin (section 0). For part 3 of step 3, calculations for rigid PUR foam production showed that a total of 1.521 mmBtu of natural gas was combusted for olefin production, 1.314 mmBtu for propylene and 0.207 mmBtu for pyrolysis gas.

2.2.15.4 Total Energy and Emissions Results[45]

Table 2.30 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from PlasticsEurope. Rigid PUR foam was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the PlasticsEurope reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.30: Comparison of Rigid PUR Foam Data

	Updated Values	Industry Source PlasticsEurope
Energy Use (mmBtu/ton)		
Total Energy	64.253	*87.260
Fossil fuels	62.804	78.748
Coal	7.899	9.553
Natural gas	36.054	37.473
Petroleum	18.851	31.720
Total Emissions(g/ton)		
VOC	570.197	10.160
CO	5578.136	4491.955
NOx	3900.995	7437.353
PM10	1839.692	3878.925
PM2.5	611.325	
SOx	13544.816	10229.836
CH4	11104.096	29397.384
N2O	35.504	9.530
CO2	2,681,401	3,073,533
CO2 (VOC, CO, CO2)	2,691,944	3,080,719
GHGs	2,980,126	3,778,080

*PlasticsEurope energy values are reported in HHV.

[45] See footnote 4 on page 12

2.2.16 Flexible Polyurethane (PUR) Foam Production

2.2.16.1 Description of Process Steps

- Extraction and refining of crude oil and natural gas.
- Manufacture of olefins (ethylene, propylene), ammonia, and toluene from processed natural gas and refined oil.
- Mining of salt (NaCl) and production of chlorine, NaOH, and KOH.
- Manufacture of propylene oxide from propylene, oxygen, chlorine, NaCl, and NaOH.
- Manufacture of ethylene oxide from ethylene and oxygen.
- Harvesting of palm kernel to manufacture glycerine.
- Production of polyol for flexible foam from propylene oxide, ethylene oxide and KOH.
- Manufacture of phosgene from chlorine and sodium hydroxide.
- Manufacture of nitric acid from ammonia.
- Manufacture of dinitrotoluene from nitric and sulfuric acids.
- Manufacture of toluene diamine (TDA) from dinitrotoluene and hydrogen.
- Production of TDI from TDA and phosgene.
- Production of flexible polyurethane foam from polyol for flexible foam and TDI.

2.2.16.2 Data Source(s)

Although the ACC report provides data concerning precursor resins for flexible polyurethane foam, it does not address the final production stage where the precursor polyol and isocyanate, TDI, are mixed to create the flexible PUR foam. PlasticsEurope has a module that accounts for all production stages for flexible PUR foam. However, in the 2011 ACC report, Franklin Associates noted that PlasticsEurope total energy values for TDI were quite high due to incorrect allocation to HCl production. Ideally, North American data would be used, but the final stage of production should also be included. Thus a model was created where European data for the final production stage was added to the North American data for the precursors.

Primary data for ethylene and propylene production were gathered from eight thermal-cracking units in the U.S. and Canada for production year 2003. Primary data for oxygen manufacture were gathered from three producers in the North America for production years 1990-1993. Primary data for ethylene oxide manufacture were gathered from six producers in the U.S. and Europe for production years 1990-1992. PlasticsEurope provided the data for mining of NaCl. Primary data for chlorine production were gathered from three plants in the U.S. for production year 2003. Primary data for polyether polyol for flexible foam manufacture were gathered from five plants in the U.S. for production years 2003 and 2005. Primary data for nitric acid fabrication were gathered from a European source in 1990. Primary data for toluene manufacture were collected from two European producers in the early 1990’s. Primary data for dinitrotoluene production were gathered from one U.S. source. Primary data for TDA production were gathered from two sources in the U.S. for production year 2003. Primary data for TDI production were gathered from three plants in the U.S. for production year 2003. Primary data for flexible PUR foam production were gathered from one European site in 1996.

<u>Data Quality</u>

In order to get dataset for final production stage energy and emissions due to precursor production had to be subtracted out using European data from PlasticsEurope eco-profiles for TDI and polyol. An assumption had to be made, based on the flexible PUR foam eco-profile, about how much TDI and polyol was used in the flexible foam production. If the weight factors used in the calculations were incorrect, or the division between precursor and foam production was not exact, errors in the total energy and emissions would result.

2.2.16.3 Data Preparation for GREET

The following steps were used to prepare data for flexible PUR foam production from the ACC report and PlasticsEurope eco-profiles for use in the GREET model.

1. **Preparation of North American precursor data:** Feedstock, process, and transportation energy values as well as non-combustion emissions for each precursor were weighted and added together.
   - Physical units of purchased energy for feedstock, process, and transportation energy were drawn from Table L-1 and N-1 of the ACC report appendices for flexible foam polyol and TDI, respectively.
   - Internal offgas and recovered energy values were also taken from the "Total Energy" column from appendices Table L-1 and N-1.
   - Energy data for each precursor were manipulated to convert reference flow from 1000 lbs resin to 2000 lbs (1 ton) resin.
   - Non-combustion emissions data were taken from the "process emissions" column from Table 12-4 and Table 14-4 from the ACC report for polyol and TDI and converted to grams per ton of resin.
   - The polyol and TDI datasets, including emissions, were multiplied by 0.713 and 0.285, respectively, and then summed.

2. **Preparation of European final production stage data:** Feedstock, process, and transportation energy values as well as non-combustion emissions for each precursor were weighted and added together, then subtracted from the full rigid PUR foam dataset.
   - Energy use data preparation step 1, parts 1-4, for nylon 66 resin (section 2.2.11.3) were followed using PlasticsEurope data from Table 1 of the polyol and TDI eco-profiles and Table 3 of the flexible PUR foam production eco-profile.
   - Non-combustion emissions data were drawn from the "from process" column in Table 6 of the polyol and TDI eco-profiles and Table 8 of the flexible PUR foam eco-profile and converted to grams per ton of resin.
   - Datasets, including emissions, for polyol and TDI were multiplied by, respectively, and subtracted from the flexible PUR foam dataset.

3. **Combination of the North American precursor and European final production stage data:** Data calculated for North American precursors and European final production stage were summed.
   - The North American precursor dataset resulting from step 4 above was added to the European dataset resulting from step 6 above.
   - Energy values were converted from physical units to mmBtu/ton resin using LHV factors found in GREET 1.8.c.
   - Recovered energy was excluded from the total "energy use" as it was not possible to model in GREET using the data currently available, and it comprises only 1-2% of total "energy use." Biomass energy was also excluded for reasons similar to those for recovered energy.
   - Final data preparation was the same as step 3 for HDPE resin (section 0). For part 3 of step 3, calculations for flexible PUR foam production showed that a total of 2.394 mmBtu of

natural gas was combusted for olefin production, 0.284 mmBtu for ethylene and 2.111 mmBtu for propylene.

2.2.16.4 Total Energy and Emissions Results[46]

Table 2.31 shows total energy and emissions results using updated values. Also presented are total energy and emissions results from PlasticsEurope. Flexible PUR foam was not previously included in GREET, so no comparison is possible between updated and previous results. Note that the PlasticsEurope reported HHV for total energy. This would account for a 5-10% difference in updated and industry results.

Table 2.31: Comparison of Flexible PUR Foam Data

	Updated Values	Industry Source PlasticsEurope
Energy Use (mmBtu/ton)		
Total Energy	68.704	*87.824
Fossil fuels	67.081	77.681
Coal	8.394	9.447
Natural gas	42.352	38.456
Petroleum	16.335	29.777
Total Emissions(g/ton)		
VOC	627.918	5.207
CO	5216.203	4897.114
NOx	3919.177	8358.749
PM10	1907.986	5774.393
PM2.5	617.765	
SOx	14442.348	11612.792
CH4	13066.711	29588.073
N2O	38.040	17.595
CO2	3,009,784	3,523,618
CO2 (VOC, CO, CO2)	3,019,938	3,531,433
GHGs	3,357,942	4,227,904

*PlasticsEurope energy values are reported in HHV.

2.2.17 Blow Molding of HDPE Bottles

2.2.17.1 Description of Process Steps

- Heat HDPE resin.
- Extrude molten polymer as a tube into a mold.
- Inject compressed air into the mold, forcing the resin to the sides of the mold.
- Chill the mold with water to solidify the HDPE product and eject from mold.

2.2.17.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for blow molding of HDPE bottles. No other publicly available source of blow molding data provides the level of detail necessary for use in the GREET model.

Primary data for blow molding of HDPE bottles were gathered from two European manufacturing sites in 1998.

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[46] See footnote 4 on page 12

Data Quality

PlasticsEurope report that few non-combustion emissions result from the transformation process itself. Thus, although a separate list of non-combustion emissions was not made available for HDPE blow molding, the effects on the overall results are expected to be minimal.

2.2.17.3 Data Preparation for GREET

The following steps were used to prepare data for HDPE blow molding from PlasticsEurope for use in the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. The following fuel categorizes were used:
    - Electricity
    - Diesel
    - Gas oil (as diesel)
    - Propane (as LPG)

- Purchased process energy was drawn from Table 1 in the HDPE Bottles eco-profile. Propane was modeled as LPG and gas oil was modeled as diesel.
- Data were manipulated to convert reference flow from 1 kg of transformed product to 1 ton of transformed product.
- Energy values were converted from HHV in MJ to physical U.S. customary units using HHV factors for each fuel found in GREET 1.8.c.
- Energy values were converted from physical units to mmBtu per ton of blow molded HDPE bottles using LHV factors found in GREET 1.8.c.

2.2.17.4 Total Energy and Emissions Results[47]

Table 2.32 shows total energy and emissions results for blow molding of HDPE bottles. Results do not include energy use or emissions from resin or additive production, packaging, or transport. HDPE blow molding was not previously included in GREET, so no comparison is possible between updated and previous results.

[47] See footnote 4 on page 12

Table 2.32: HDPE Blow Molding Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	13.596
Fossil fuels	11.760
Coal	8.575
Natural gas	2.834
Petroleum	0.351
Total Emissions(g/ton)	
VOC	100.454
CO	291.882
NOx	1193.038
PM10	1520.841
PM2.5	399.732
SOx	2618.289
CH4	1521.840
N2O	14.887
CO2	1,129,300
CO2 (VOC, CO, CO2)	1,130,071
GHGs	1,172,554

2.2.18 Calendaring of PVC Film

2.2.18.1 Description of Process Steps

- Preheat PVC resin.
- Pass PVC resin between a series of heated rollers to create a sheet of even thickness.
- Pass PVC film between cooling rollers.
- Trim film and wind into a final roll.

2.2.18.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for calendaring of PVC film. No other publicly available source of PVC calendaring data provides the level of detail necessary for use in the GREET model.

Primary data for calendaring of PVC film were gathered from one German manufacturing site for production year 2007.

2.2.18.3 Data Preparation for GREET

The following steps were used to prepare data from the PlasticsEurope PVC film calendaring eco-profile for use in the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. The following fuel categorizes were used:
    - o Electricity
   - Purchased process energy values were found in Table 1.
   - Data were manipulated to convert reference flow from 1 kg to 1 ton of transformed product.
   - Energy data were converted from MJ to kWh and then to mmBtu/ton of calendared PVC film.

2. **Add Non-combustion emissions:** The data presented in the PVC film calendaring eco-profile reported "emissions to air," referred to here as non-combustion emissions, from the transformation process. Non-combustion emissions were reported in GREET.
   - Non-combustion emissions data were found in Table 1.
   - Non-combustion emissions were converted to g/ton of calendared PVC film.

2.2.18.4 Total Energy and Emissions Results[48]

Table 2.33 shows total energy and emissions results for calendaring of PVC film. Results do not include energy use or emissions from resin or additive production, packaging, or transport. PVC calendaring was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.33: PVC Film Calendaring Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	4.611
Fossil fuels	3.987
Coal	2.914
Natural gas	0.962
Petroleum	0.111
Total Emissions(g/ton)	
VOC	34.003
CO	100.211
NOx	403.750
PM10	554.489
PM2.5	135.717
SOx	887.983
CH4	516.323
N2O	5.049
CO2	382,856
CO2 (VOC, CO, CO2)	383,120
GHGs	397,532

2.2.19 Extrusion of HDPE Pipe

2.2.19.1 Description of Process Steps

- Heat HDPE resin.
- Extrude molten resin through an annular die.
- Pass extruded HDPE pipe through water to cool.

2.2.19.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for extrusion of HDPE pipe. No other publicly available source of HDPE extrusion data provides the level of detail necessary for the use in GREET model.

Primary data for extrusion of HDPE pipe were gathered from three European manufacturing sites for production year 2007.

[48] See footnote 4 on page 12

2.2.19.3 Data Preparation for GREET

The following steps were used to prepare data from the PlasticsEurope pipe extrusion eco-profile for use in the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. The following fuel categorizes were used:
    - o Electricity
- Purchased process energy data were found in Table 2 in the pipe extrusion eco-profile.
- Data were manipulated to convert reference flow from 1 kg to 1 ton of transformed product.
- Electricity data were converted from MJ to kWh and then to mmBtu/ton of extruded HDPE pipe.

2.2.19.4 Total Energy and Emissions Results[49]

Table 2.34 shows total energy and emissions results for extrusion of HDPE pipe. Results do not include energy use or emissions from resin or additive production, packaging, or transport. HDPE extrusion was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.34: HDPE Pipe Extrusion Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	4.347
Fossil fuels	3.759
Coal	2.747
Natural gas	0.907
Petroleum	0.105
Total Emissions(g/ton)	
VOC	32.055
CO	92.474
NOx	380.607
PM10	486.988
PM2.5	127.943
SOx	837.100
CH4	486.745
N2O	4.760
CO2	360,903
CO2 (VOC, CO, CO2)	361,148
GHGs	374,735

2.2.20 Extrusion of PVC Pipe

2.2.20.1 Description of Process Steps

- Preheat PVC resin.
- Extrude molten resin through an annular die.
- Pass extruded PVC pipe through water to cool.

[49] See footnote 4 on page 12

2.2.20.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for extrusion of PVC pipe. No other publicly available source of PVC extrusion data provides the level of detail necessary for use in the GREET model.

Primary data for extrusion of PVC pipe were gathered from four European manufacturing sites for production year 2007.

2.2.20.3 Data Preparation for GREET

Data preparation for the PVC pipe extrusion followed the same procedure as for HDPE pipe extrusion (section 0) except that data was taken from Table 1 of the pipe extrusion eco-profile.

2.2.20.4 Total Energy and Emissions Results[50]

Table 2.35 shows total energy and emissions results for extrusion of PVC pipe. Results do not include energy use or emissions from resin or additive production, packaging, or transport. PVC extrusion was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.35: PVC Pipe Extrusion Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	4.188
Fossil fuels	3.621
Coal	2.646
Natural gas	0.874
Petroleum	0.101
Total Emissions(g/ton)	
VOC	30.883
CO	89.091
NOx	366.685
PM10	469.175
PM2.5	123.263
SOx	806.480
CH4	468.941
N2O	4.586
CO2	347,701
CO2 (VOC, CO, CO2)	347,937
GHGs	361,027

2.2.21 Extrusion of PP Pipe

2.2.21.1 Description of Process Steps

- Preheat PP resin.
- Extrude molten resin through an annular die.
- Pass extruded PP pipe through water to cool.

2.2.21.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for extrusion of PP pipe. No other publicly available source of PP extrusion data provides the level of detail necessary for use in the GREET model.

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[50] See footnote 4 on page 12

Primary data for extrusion of PP pipe were gathered from three European manufacturing sites for production year 2007.

2.2.21.3 Data Preparation for GREET

Data preparation for the PP pipe extrusion followed the same procedure as for HDPE pipe extrusion (section 0) except that data was taken from Table 3 of the pipe extrusion eco-profile.

2.2.21.4 Total Energy and Emissions Results[51]

Table 2.36 shows total energy and emissions results for extrusion of PP pipe. Results do not include energy use or emissions from resin or additive production, packaging, or transport. PP extrusion was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.36: PP Pipe Extrusion Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	5.560
Fossil fuels	4.808
Coal	3.513
Natural gas	1.160
Petroleum	0.134
Total Emissions(g/ton)	
VOC	41.001
CO	118.279
NOx	486.817
PM10	622.885
PM2.5	163.646
SOx	1070.698
CH4	622.574
N2O	6.088
CO2	461,615
CO2 (VOC, CO, CO2)	461,928
GHGs	479,307

2.2.22 Injection Molding of HDPE

2.2.22.1 Description of Process Steps

- Heat HDPE resin.
- Inject molten resin into a mold.
- Cool mold with water and eject HDPE product from mold once solid.

2.2.22.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for injection molding of HDPE. No other publicly available source of HDPE injection molding data provides the level of detail necessary for use in the GREET model.

Primary data for injection molding of HDPE were gathered from three European manufacturing sites for production year 2007.

[51] See footnote 4 on page 12

2.2.22.3 Data Preparation for GREET

Data preparation for the HDPE injection molding followed the same procedure as for HDPE pipe extrusion (section 0) except that data was taken from Table 2 of the injection molding eco-profile.

2.2.22.4 Total Energy and Emissions Results[52]

Table **2.37** shows total energy and emissions results for injection molding of HDPE. Results do not include energy use or emissions from resin or additive production, packaging, or transport. HDPE injection molding was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.37: HDPE Injection Molding Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	15.862
Fossil fuels	13.715
Coal	10.022
Natural gas	3.310
Petroleum	0.383
Total Emissions(g/ton)	
VOC	116.969
CO	337.434
NOx	1388.821
PM10	1777.002
PM2.5	466.858
SOx	3054.551
CH4	1776.118
N2O	17.368
CO2	1,316,922
CO2 (VOC, CO, CO2)	1,317,817
GHGs	1,367,395

2.2.23 Injection Molding of PVC

2.2.23.1 Description of Process Steps

- Heat PVC resin.
- Inject molten resin into a mold.
- Cool mold with water and eject PVC product from mold once solid.

2.2.23.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for injection molding of PVC. No other publicly available source of PVC injection molding data provides the level of detail necessary for use in the GREET model.

Primary data for injection molding of PVC were gathered from four European manufacturing sites for production year 2007.

[52] See footnote 4 on page 12

2.2.23.3 Data Preparation for GREET

Data preparation for the PVC injection molding followed the same procedure as for HDPE pipe extrusion (section 0) except that data was taken from Table 1 of the injection molding eco-profile.

2.2.23.4 Total Energy and Emissions Results[53]

Table 2.38 shows total energy and emissions results for injection molding of PVC. Results do not include energy use or emissions from resin or additive production, packaging, or transport. PVC injection molding was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.38: PVC Injection Molding Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	9.753
Fossil fuels	8.433
Coal	6.163
Natural gas	2.035
Petroleum	0.235
Total Emissions(g/ton)	
VOC	71.922
CO	207.480
NOx	853.951
PM10	1092.634
PM2.5	287.059
SOx	1878.166
CH4	1092.090
N2O	10.679
CO2	809,742
CO2 (VOC, CO, CO2)	810,292
GHGs	840,777

2.2.24 Injection Molding of PP

2.2.24.1 Description of Process Steps

- Heat PP resin.
- Inject molten resin into a mold.
- Cool mold with water and eject PP product from mold once solid.

2.2.24.2 Data Source(s)

PlasticsEurope was determined to have the best available life cycle inventory data for injection molding of PP. No other publicly available source of PP injection molding data provides the level of detail necessary for use in the GREET model.

Primary data for injection molding of PP were gathered from three European manufacturing sites for production year 2007.

[53] See footnote 4 on page 12

2.2.24.3 Data Preparation for GREET

Data preparation for the PP injection molding followed the same procedure as for HDPE pipe extrusion (section 0) except that data was taken from Table 3 of the injection molding eco-profile.

2.2.24.4 Total Energy and Emissions Results[54]

Table 2.39 shows total energy and emissions results for injection molding of PP. Results do not include energy use or emissions from resin or additive production, packaging, or transport. PP injection molding was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.39: PP Injection Molding Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	6.345
Fossil fuels	5.486
Coal	4.009
Natural gas	1.324
Petroleum	0.153
Total Emissions(g/ton)	
VOC	46.788
CO	134.974
NOx	555.529
PM10	710.801
PM2.5	186.743
SOx	1221.820
CH4	710.447
N2O	6.947
CO2	526,769
CO2 (VOC, CO, CO2)	527,127
GHGs	546,958

2.2.25 Compression Molding

2.2.25.1 Description of Process Steps

- Heat resin.
- Extrude molten resin through an annular die.
- Pass extruded polymer through water to cool.
- Slicing and finishing of extruded polymer.
- Molding, curing, and finishing of polymer.

2.2.25.2 Data Source(s)

In a 2010 Argonne National Laboratory study, Sullivan, Burnham, and Wang modeled the energy use and emissions resulting from vehicle component manufacture, including transformation processes for plastics.[55] The authors drew process energy data for tire and inner tube molding from *Energy Analysis of*

[54] See footnote 4 on page 12

[55] Sullivan, J. L., Burnham, A., and Wang, M. (2010) *Energy-Consumption and Carbon-Emission Analysis of Vehicle Component Manufacturing*. ANL/ESD/10-6. Argonne, IL: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.

108 Industrial Processes, a book published in 1980, in order to model compression molding of plastics.[56] No other publicly available source of data for compression molding was found to provide the level of detail necessary for use in the GREET model.

Data Quality

While the data seems to be of high-quality, significant change to the process may have occurred since that time. Thus, the data may not reflect current industry practices for rubber or compression molding.

2.2.25.3 Data Preparation for GREET

The following steps were used to prepare data from the 2010 ANL model for use in the GREET model.

1. **Add fuel energy:** The energy associated with process fuels was summed to find the "energy use" input for GREET. The following fuel categorizes were used:
    - o Electricity
- Purchased process energy was found in Table A-2.
- Data were manipulated to convert reference flow from 1 kg to 1 ton of transformed product.
- Electricity data were converted from kWh to mmBtu/ton of compression molded polymer.

2.2.25.4 Total Energy and Emissions Results[57]

Table 2.40 shows total energy and emissions results for rubber molding. Results do not include energy use or emissions from resin or additive production, packaging, or transport. Rubber molding was not previously included in GREET, so no comparison is possible between updated and previous results.

Table 2.40 Compression Molding Data

	Updated Values
Energy Use (mmBtu/ton)	
Total Energy	9.780
Fossil fuels	9.071
Coal	3.310
Natural gas	5.617
Petroleum	0.144
Total Emissions(g/ton)	
VOC	69.882
CO	214.887
NOx	798.981
PM10	602.408
PM2.5	169.543
SOx	1055.986
CH4	1423.691
N2O	10.760
CO2	708,201
CO2 (VOC, CO, CO2)	708,756
GHGs	747,555

[56] Brown, H. L., Hamel, B. B., Hedman, B. A., Koluch, M., Gajanana, B. C., and Troy, P. (1996) Energy Analysis of 108 Industrial Processes, Fairmount Press.

[57] See footnote 4 on page 12

2.2.26 Average Transformed Plastic Products

2.2.26.1 Description of Process Steps

- Transformation of plastic resins into semi-finished products via blow molding, calendaring, extrusion, injection molding, and compression molding.

2.2.26.2 Data Source(s)

The USAMP study[58] provided data on the percent by weight of each type of plastic in an average family sedan. Even though this data represents plastic composition of a car in 1995, more recent data was not found.

In a 2010 Argonne National Laboratory study, Sullivan, Burnham, and Wang modeled the energy use and emissions resulting from vehicle component manufacture. Data were presented for the percent of curb weight of each transformation type for a given plastic resin. If data for the actual transformation process was not available, the best surrogate transformation method was indicated.

2.2.26.3 Data Preparation for GREET

The following steps were taken to combine resin production and plastic transformation modules to model the energy use and emissions of semi-finished plastic products.

1. **Calculation of transformation weights:** Determine how much each transformation type is used to convert each plastic resin into 1 ton of transformed plastic product.
    - The percent of curb weight for each transformation of a particular resin was drawn from Table A-1 in the appendices of the 2010 ANL study. No data was available for HIPS, GPPS, or epoxy, so no transformations were applied to those resins.
    - The percent of curb weight of each resin was acquired from Table 2 of the USAMP study.
    - To find the share of each transformation type used on each plastic resin, the percent of curb weight for each transformation of a given resin was divided by the percent of curb weight of each resin. (See Table 2.41)

2. **Calculation of the average plastic product:** The energy and emissions profile of an average ton of transformed plastic was calculated.
    - The total energy and emissions datasets for each transformation was weighted by the resulting percentages from step 1 above for each resin and added to the total energy and emissions datasets for the production of each resin.
    - Material input into each transformation process was calculated from PlasticsEurope data. Any minor resins and other additives were summed together with the dominant resin and modeled as such. The mass input factors are shown in Table 2.42.
    - The weights for polyethylene (PE) were applied to HDPE, LDPE, and LLDPE.

[58] Sullivan, J., et al (1998) Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project. Society of Automotive Engineers. SAE #982160.

Table 2.41: Weights for Transformations for Each Resin, % by weight

	PP	PVC	Nylon 66	ABS	EPDM	PE	PC	PET	Nylon 6
Blow Molding	9.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	36.4%
Calendering	0.0%	18.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Compression Molding	15.3%	1.5%	34.3%	23.8%	31.9%	24.3%	22.0%	50.0%	45.4%
Extrusion (HDPE)	0.0%	0.0%	29.9%	17.5%	27.5%	9.3%	0.0%	0.0%	0.0%
Extrusion (PVC)	0.0%	51.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Extrusion (PP)	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Inj. Molding (HDPE)	0.0%	0.0%	0.0%	0.0%	0.0%	66.5%	0.0%	0.0%	0.0%
Inj. Molding (PVC)	0.0%	29.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Injection Molding (PP)	73.6%	0.0%	35.8%	58.7%	40.6%	0.0%	78.0%	50.0%	18.2%

Table 2.42: Mass of Resin Input into Plastics Transformation Processes

	Tons of Resin Input per Ton of Transformed Product
Blow Molding	1.0003
Calendaring	1.1554
Compression Molding	1.0000
Extrusion (HDPE)	0.9459
Extrusion (PVC)	1.0024
Extrusion (PP)	1.0018
Injection Molding (HDPE)	1.0056
Injection Molding (PVC)	1.0307
Injection Molding (PP)	1.1393

3. **Calculation of fiber-reinforced plastics:** Glass fiber-reinforced plastic (GFRP) and carbon fiber-reinforced plastic (CFRP) modules were developed using liquid epoxy resin in addition to existing GREET datasets for glass fiber, carbon fiber, and a reinforced plastic fabrication. Epoxy is a common thermosetting polymer used in glass and carbon fiber-reinforced plastics and was used as a representative resin for all thermosetting plastics used in GFRP or CFRP.
   - The epoxy and glass fiber modules were weighted and summed according to the percent composition seen in Table 2.43, which was taken from GREET 2.7.
   - The epoxy module and carbon fiber modules were weighted and summed according to the percent composition seen in Table 2.43.
   - The combined datasets were then multiplied by a factor of 1.140 to adjust for the tons of intermediate product needed for 1 ton of final GFRP or CFRP product.
   - The module for reinforced plastic fabrication found in GREET 2.7 was added to both of the datasets resulting from the previous step to account for the final transformation stages of the reinforced plastics.

Table 2.43: Composition of GFRP and CFRP, % by weight

	Epoxy	Fiber	Tons of Intermediate Material Needed for 1 Ton of Final Reinforced Plastic Product
GFRP	50.0%	50.0%	1.140
CFRP	70.0%	30.0%	1.140

2.2.26.4 Total Energy and Emissions Results[59]

Table 2.44: Results for an Average Ton of Transformed HDPE, LDPE, and LLDPE

	HDPE Average	LDPE Average	LLDPE Average
Energy Use (mmBTU/ton)			
Total Energy	76.928	81.543	76.740
Fossil fuels	74.890	79.489	74.757
Coal	9.523	9.596	9.266
Natural gas	55.843	60.369	56.013
Petroleum	9.524	9.524	9.477
Total Emissions(g/ton)			
VOC	858.958	902.888	863.810
CO	3251.672	3336.983	3295.765
NOx	2152.937	2395.119	2921.624
PM10	1868.675	1878.519	1799.084
PM2.5	491.890	497.341	475.143
SOx	24230.925	24711.985	24717.936
CH4	16595.700	17464.853	16607.798
N2O	29.776	34.979	44.630
CO2	2,368,420	2,605,322	3,473,744
CO2 (VOC, CO, CO2)	2,376,207	2,613,380	3,481,615
GHGs	2,799,972	3,060,425	3,910,110

Table 2.45: Results for an Average Ton of Transformed PP, PET, and PVC

	PP Average	PET Average	PVC Average
Energy Use (mmBTU/ton)			
Total Energy	76.574	67.496	54.542
Fossil fuels	75.182	65.683	52.796
Coal	6.507	9.249	8.612
Natural gas	48.394	29.381	39.370
Petroleum	20.282	27.053	4.814
Total Emissions(g/ton)			
VOC	746.481	416.088	539.951
CO	6511.362	13725.424	1923.840
NOx	2148.137	3211.003	2478.877
PM10	1314.915	1932.075	1692.034
PM2.5	344.143	611.258	477.222
SOx	21694.811	10416.232	12958.041
CH4	15275.279	10976.994	10764.487
N2O	26.574	39.764	34.117
CO2	2,011,848	2,811,167	2,393,428
CO2 (VOC, CO, CO2)	2,024,407	2,834,032	2,398,134
GHGs	2,414,208	3,120,307	2,677,413

[59] See footnote 4 on page 12

Table 2.46: Results for an Average Ton of Transformed ABS and EPDM

	ABS Average	EPDM Average
Energy Use (mmBTU/ton)		
Total Energy	96.672	77.639
Fossil fuels	94.600	76.675
Coal	11.124	4.509
Natural gas	54.244	57.428
Petroleum	29.232	14.738
Total Emissions(g/ton)		
VOC	774.715	772.901
CO	9985.663	4012.574
NOx	4405.147	1380.159
PM10	2319.824	933.647
PM2.5	698.555	235.342
SOx	20364.137	22527.874
CH4	16885.405	15227.412
N2O	43.119	17.854
CO2	3,452,226	1,592,353
CO2 (VOC, CO, CO2)	3,470,332	1,601,067
GHGs	3,905,317	1,987,073

Table 2.47: Results for an Average Ton of Transformed Nylon 66, Nylon 6, and PC

	Nylon 66 Average	Nylon 6 Average	PC Average
Energy Use (mmBTU/ton)			
Total Energy	115.596	105.099	99.411
Fossil fuels	112.339	102.499	96.348
Coal	15.217	12.148	14.750
Natural gas	63.503	59.810	44.132
Petroleum	33.618	30.540	37.466
Total Emissions(g/ton)			
VOC	507.997	494.302	446.021
CO	3346.892	6923.317	1576.575
NOx	9049.238	15269.202	6545.505
PM10	3407.088	2888.554	3058.853
PM2.5	1073.209	987.238	1010.204
SOx	10217.808	10360.639	8587.240
CH4	12832.300	13069.752	9740.248
N2O	777.130	8103.407	82.501
CO2	6,098,173	6,217,644	4,745,111
CO2 (VOC, CO, CO2)	6,105,016	6,230,064	4,748,979
GHGs	6,657,408	8,971,623	5,017,070

Table 2.48: Results for 1 Ton of Final GFRP and CFRP Product

	Glass Fiber-Reinforced Plastic Average	Carbon Fiber-Reinforced Plastic Average
Energy Use (mmBTU/ton)		
Total Energy	72.677	137.937
Fossil fuels	70.727	135.770
Coal	9.137	10.346
Natural gas	46.399	80.522
Petroleum	15.192	44.902
Total Emissions(g/ton)		
VOC	379.435	766.683
CO	2074.228	2901.387
NOx	10863.583	12374.462
PM10	5126.528	7845.488
PM2.5	736.654	1653.069
SOx	9702.409	12775.011
CH4	9199.739	17503.488
N2O	63.373	112.754
CO2	4,085,748	8,323,559
CO2 (VOC, CO, CO2)	4,090,190	8,330,508
GHGs	4,339,068	8,801,696

3 Summary of Total Energy and Greenhouse Gas Emissions

The total energy and total GHG emissions resulting from modeling the raw materials along with the respective material transformations in GREET are shown in Table 3.1.

Table 3.1: Summary of Total Energy and GHG Emissions by Raw Material[60]

	Calculated Results		GREET 2.7	
	Total Energy	GHG Emissions	Total Energy	GHG Emissions
	mmBtu/ton	grams/ton	mmBtu/ton	grams/ton
Steel Product				
Primary	51.189	4,060,444	38.771	4,899,199
Secondary	20.441	1,677,140	29.337	2,056,470
Aluminum Product				
Cast Aluminum (Primary)	115.352	9,850,535	132.856	9,173,556
Extruded Aluminum (Primary)	111.635	9,633,395		
Wrought Aluminum (Primary)	122.985	10,533,730	157.507	11,023,858
Nickel Product				
Primary	181.208	13,825,194	127.174	10,709,097
Copper Product				
Primary	43.299	3,030,844	95.706	7,691,790
Plastics Product				
HDPE	77.01	2,802,119	45.977	3,521,214
LDPE	81.631	3,062,905		
LLDPE	81.631	3,913,680		
PP	70.152	2,248,634	42.063	3,256,624
PET	63.626	2,959,275		
PVC	52.748	2,597,512		
ABS	90.613	3,680,061		
PS	74.809	1,930,118		
Nylon 6	63.626	2,959,275		
Nylon 66	112.054	6,458,801		
PC	90.364	4,583,301		
EPDM	74.809	1,930,118		
PUR (Rigid Foam)	64.253	2,980,126		
PUR (Flexible Foam)	68.704	3,357,942		
Fiber Reinforced Plastic				
Glass Fiber Reinforced	72.677	4,339,068	63.266	5,200,982
Carbon Fiber Reinforced	137.937	8,801,696	130.423	10,437,082

Results from this project vary from existing GREET values based on a variety of factors including difference in source data, alternative modeling approaches, and data gaps. A more detailed discussion of sources of discrepancy can be found in Section 1.3. In general, it is difficult to determine the cause of discrepancy when comparing to the existing GREET model because of a lack of documentation.

4 Discussion of Results for Future GREET Updates

In this project, raw material production and transformation processes were modeled using best available data. The degree to which the results of this project are representative of these processes as

[60] See footnote 4 on page 12

well as guidance to Argonne National Laboratory for using these results to update GREET are discussed briefly by material type.

- Steel

The steel results were based on data from the Athena Sustainable Materials. While the data were not recent (1993-2003), the report is relatively comprehensive and transparent. As such, it is believed that the inclusion of the steel results from this project would improve the model. In the future, if sufficiently detailed data were made available from the World Steel Association, these data would likely be preferable to the Athena data because it is significantly more recent.

- Aluminum

The primary aluminum data came from *Life Cycle Impact Assessment of Aluminum Beverage Cans (2010)* report, which is believed to be the most representative of the industry. Secondary aluminum production as well as transformation processes were based on data from the Aluminum Association Report, *Life Cycle Inventory Report for the Aluminum Industry (1998)*. While the data are not very current, the report is very detailed and remains a good resource for updating the GREET model.

- Nickel

The nickel results from this project are not believed to be very representative of current nickel production. They are based on data from the Nickel Institute which are aggregated to include upstream energy and are outdated. The Nickel Institute is planning to collect new data in 2012, with intentions of publishing new results in 2013. These updated data should be reviewed and considered for use in the GREET model.

- Copper

International Copper Association (ICA) is preparing to publish life cycle inventory data shortly. Unfortunately, these data were not available in time to include in this project. They should be reviewed for considered for inclusion into GREET as they would likely be preferable to results from this project, which likely underestimate energy and emission burdens.

- HDPE, LDPE, LLDPE, PP, PET, GPPS, HIPS, PVC, ABS

The results for these plastics were based on data from the American Chemistry Council, which were compiled by Franklin Associates. The ACC report and appendix demonstrates a high degree of rigor, detail, and transparency, and as such was a strong source for updating GREET. A revised report from Franklin with updated mass balance flows is anticipated soon. It is advisable that the GREET update reflect the revised data when it becomes available.

- Nylon 6, Nylon 66, Liquid Epoxy Resin, Polycarbonate

The results for these plastics were based on data from PlasticsEurope, assembled by several well-known LCA practitioners. PlasticsEurope receives data from many plastics manufacturers throughout Europe and continually updates their plastics eco-profiles. Thus, the data for these plastics are recommended for use in the GREET model. However, PC energy use was only provided in terms of primary energy and purchased energy had to be back calculated. Updates to nylon 6, nylon 66, liquid epoxy, and PC modules in GREET should be made as new eco-profiles are made available by PlasticsEurope.

- EPDM

The results of this resin were based on current data from the American Chemistry Council, which were compiled by Franklin Associates. Due to the rigor of the ACC plastics data, this was considered to be a good representation of EPDM. As no data for ethylidene norbornene was available; its precursor butadiene was used as substitute. If data for ethylidene norbornene becomes available, it should be used to replace the butadiene portion of the model. Additionally, it is advisable that the GREET update reflect the modified data from the revised ACC data when it becomes available.

- Rigid PUR foam, Flexible PUR foam

Rigid and flexible PUR foam results were based on a hybrid of North American PUR precursor and European final foam production stage data due to the lack of final foam production stage data for North American producers and incorrect HCl allocation in PlasticsEurope's TDI and MDI data. Since assumptions of material composition were used to create the hybrid PUR foam models for this report, a new, corrected version of PlasticsEurope's full rigid and flexible PUR foam production eco-profiles would likely be a better representation of PUR foam production.

Center for Sustainable Systems
University of Michigan

APPENDIX: Life Cycle Material Data Update for GREET Model

Index

Metals Data **Pg Number**

Plastics Data

Limestone Extraction and Processing

Reference Unit:	1 ton of Lime/Limestone Mix
Principal Data Source(s):	Athena Sustainable Material Insititute
Geographic Location:	Canada and US
Timeframe:	c. 1993-2003
Description:	

Mix is approx 45% Limestone, 39% Burnt Lime, 16% Dolomite

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	0.232	gal	0.030
Natural gas	3082.719	cu ft	3.030
Coal		lb	
Electricity	29.818	kWh	0.102
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas		cu ft	
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx	630.247	g	
CH4		g	
N2O		g	
CO2	419922.463	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Ore Extraction and Processing

Reference Unit:	1 ton of processed/pelletized iron ore
Principal Data Source(s):	Athena Sustainable Material Insititute
Geographic Location:	Canada and US
Timeframe:	c. 1993-2003
Description:	

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units Value	Unit	Energy Content (MMBtu)
Resid. oil	1.19	gal	0.167
Diesel	0.22	gal	0.028
Natural gas	179.32	cu ft	0.176
Coal		lb	
Electricity	368.56	kWh	1.258
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas		cu ft	
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC	0.218	g	
CO	1.770	g	
NOx	3.541	g	
PM10		g	
PM2.5		g	
SOx	0.354	g	
CH4		g	
N2O		g	
CO2	218.261	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Coke Production

Reference Unit: 1 ton of coke
Principal Data Source(s): Athena Sustainable Material Insititute
Geographic Location: Canada and US
Timeframe: c. 1993-2003
Description:

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	110.509	kWh	0.377
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed	3618.788	lb	35.367
MISC: Coke	-1814.370	lb	-25.674
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas	5896.375	cu ft	2.829
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)	-14729.682	cu ft	-7.068
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC	3378.403	g	
CO	750.047	g	
NOx	401.811	g	
PM10	1515.402	g	
PM2.5	757.701	g	
SOx	2353.465	g	
CH4		g	
N2O		g	
CO2	6708.333	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Sintering

Reference Unit:	1 ton of sinter
Principal Data Source(s):	Athena Sustainable Material Insititute
Geographic Location:	Canada and US
Timeframe:	c. 1993-2003
Description:	

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	115.325	kWh	0.394
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke	70.911	lb	1.003
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas	334.217	cu ft	0.160
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC	308.250	g	
CO	20268.449	g	
NOx	112.051	g	
PM10	1859.729	g	
PM2.5	929.865	g	
SOx	220.105	g	
CH4		g	
N2O		g	
CO2	190377.123	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Blast Furnace

Reference Unit:	1 ton of liquid iron
Principal Data Source(s):	Athena Sustainable Material Insititute
Geographic Location:	Canada and US
Timeframe:	c. 1993-2003
Description:	

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	105.069	kWh	0.359
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed	9.798	gal	1.271
MISC: NG as feed	348.077	cu ft	0.342
MISC: Coal as feed		lb	
MISC: Coke	802.721	lb	11.359
MISC: Blast furnace gas	45665.107	cu ft	3.958
MISC: Coke oven gas	1382.656	cu ft	0.663
MISC: Blast furnace gas (credit)	-48158.125	cu ft	-4.174
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC	1282.961	g	
CO	16616.418	g	
NOx	13.795	g	
PM10	7.211	g	
PM2.5		g	
SOx	1374.512	g	
CH4		g	
N2O		g	
CO2	52215.772	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Basic Oxygen Furnace

Reference Unit:	1 ton of liquid steel
Principal Data Source(s):	Athena Sustainable Material Insititute
Geographic Location:	Canada and US
Timeframe:	c. 1993-2003
Description:	

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	37.614	cu ft	0.037
Coal		lb	
Electricity	127.247	kWh	0.434
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas	102.363	cu ft	0.049
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC	0.473	g	
CO	1645.577	g	
NOx	75.620	g	
PM10	218.799	g	
PM2.5	109.399	g	
SOx		g	
CH4		g	
N2O		g	
CO2	148514.506	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Hot Rolling

Reference Unit: 1 ton of hot rolled strip (pre-skin mill)
Principal Data Source(s): Athena Sustainable Material Insititute
Geographic Location: Canada and US
Timeframe: c. 1993-2003
Description:

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units Value	Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	641.092	cu ft	0.630
Coal		lb	
Electricity	206.237	kWh	0.704
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas	363.734	cu ft	0.032
MISC: Coke oven gas	2695.830	cu ft	1.294
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas). Blast furnace gas and coke oven gas combusted in boiler plant to provide steam to process.

Skin Mill

Reference Unit: 1 ton of hot rolled sheet
Principal Data Source(s): Athena Sustainable Material Insititute
Geographic Location: Canada and US
Timeframe: c. 1993-2003
Description:

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	12.247	kWh	0.042
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas	363.734	cu ft	0.032
MISC: Coke oven gas	1.911	cu ft	0.001
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas). Blast furnace gas and coke oven gas combusted in boiler plant to provide steam to process.

Cold Rolling

Reference Unit: 1 ton of cold rolled steel
Principal Data Source(s): Athena Sustainable Material Insititute
Geographic Location: Canada and US
Timeframe: c. 1993-2003
Description:

Includes annealing, pickeling, and cleaning

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	410.324	kWh	1.400
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas	2846.530	cu ft	0.247
MISC: Coke oven gas	713.880	cu ft	0.343
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas). Blast furnace gas and coke oven gas combusted in boiler plant to provide steam to process.

Galvanizing

Reference Unit: 1 ton of galvinized sheet
Principal Data Source(s): Athena Sustainable Material Insititute
Geographic Location: Canada and US
Timeframe: c. 1993-2003
Description:

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	203.913	kWh	0.696
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas	2029.524	cu ft	0.176
MISC: Coke oven gas	2328.119	cu ft	1.117
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas). Blast furnace gas and coke oven gas combusted in boiler plant to provide steam to process.

Electric Arc Furnace

Reference Unit:	1 ton of cold rolled steel
Principal Data Source(s):	Athena Sustainable Material Insititute
Geographic Location:	Canada and US
Timeframe:	c. 1993-2003
Description:	

Scrap melted in electric arc furnace to create billets for long products

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	1210.454	cu ft	1.190
Coal		lb	
Electricity	1463.554	kWh	4.994
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke	12.031	lb	0.170
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas		cu ft	
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC	174.550	g	
CO	3010.138	g	
NOx	65.367	g	
PM10	582.365	g	
PM2.5		g	
SOx	349.639	g	
CH4	0.136	g	
N2O		g	
CO2	23340.363	g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Rod and Bar Mill

Reference Unit: 1 ton of galvinized sheet
Principal Data Source(s): Athena Sustainable Material Insititute
Geographic Location: Canada and US
Timeframe: c. 1993-2003
Description:

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units: Value	Physical Units: Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	2193.299	cu ft	2.156
Coal		lb	
Electricity	315.916	kWh	1.078
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas		cu ft	
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating values and Athena data (for coke, coke oven gas, and blast furnace gas).

Stamping

Reference Unit: 1 ton of stamped steel product
Principal Data Source(s): Data contained in GREET 2.7
Geographic Location: unknown
Timeframe: unknown
Description:

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	4382.370	cu ft	4.308
Coal		lb	
Electricity	335.587	kWh	1.145
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Oil as feed		gal	
MISC: NG as feed		cu ft	
MISC: Coal as feed		lb	
MISC: Coke		lb	
MISC: Blast furnace gas		cu ft	
MISC: Coke oven gas		cu ft	
MISC: Blast furnace gas (credit)		cu ft	
MISC: Coke oven gas (credit)		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Blast Furnace and Coke Oven Gas Combustion Factors

Principal Data Source(s): Athena Sustainable Material Insititute

	grams per mmBtu of fuel combusted	
Emissions	Coke Oven Gas	Blast Furnace Gas
VOC	1.089	
CO	9.577	14.564
NOx	135.911	115.461
PM10		2.244
PM2.5		
SOx	612.600	
CH4	0.491	
N2O		
CO2	42,209	235,042

Comparison of Virgin Steel Data

	Updated Values (Final Steel Product)	Updated Values (Hot Rolled)	Previously in GREET (Final Steel Product)	Previously in GREET (Rolled Steel)	USLCI Database (Hot Rolled)
Energy Use (mmBTU/ton)					
Total Energy	50.750	26.701	38.771	23.293	21.639
Fossil fuels	48.110	25.559	37.856	22.909	
Coal	34.272	20.186	24.233	16.691	
Natural gas	11.033	3.494	11.936	5.025	
Petroleum	2.804	1.879	1.688	1.193	
Total Emissions (g/ton)					
VOC	3,949.152	2,817.717	536.021	360.117	188.232
CO	28,666.748	20,727.160	108,869.120	81,120.454	22,594.331
NOx	4,048.560	2,042.527	3,602.296	2,237.815	2,560.439
PM10	3,872.456	2,165.683	14,593.847	10,632.276	
PM2.5	1,424.213	857.951	6,303.381	4,627.528	
SOx	10,662.420	6,077.278	1,988.177	1,023.602	3,920.672
CH4	3,386.972	1,203.032	5,181.747	2,986.783	1,024.212
N2O	28.561	10.780	30.362	16.444	
CO2	3,911,899	2,072,497	4,587,856	3,034,020	2,060,381
CO2 (VOC, CO, CO2)	3,969,255	2,113,850	4,760,607	3,162,617	
GHGs	4,062,441	2,147,138	4,899,199	3,242,187	2,085,986

Notes:

Comparison of Recycled Steel Data

	Updated Values (EAF Steel)	Previously in GREET (EAF Steel)
Energy Use (mmBTU/ton)		
Total Energy	21.108	29.337
Fossil fuels	18.901	27.564
Coal	11.455	8.281
Natural gas	7.023	18.847
Petroleum	0.423	0.436
Total Emissions (g/ton)		
VOC	927.752	202.475
CO	3,707.204	5,080.603
NOx	1,907.773	2,144.607
PM10	2,715.878	1,653.773
PM2.5	626.808	499.548
SOx	4,268.510	2,691.319
CH4	2,495.758	4,449.723
N2O	21.873	28.111
CO2	1,619,186	1,928,235
CO2 (VOC, CO, CO2)	1,627,903	1,936,850
GHGs	1,696,815	2,056,470

Notes:

Bauxite Mining

Reference Unit:	1 ton of aluminum ingot
Principal Data Source(s):	Aluminum Association - Aluminum Beverage Can LCA
Geographic Location:	North America
Timeframe:	2010

Description:

Process stage in which bauxite ore is extracted from the Earth.

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	0.324	gal	0.045
Diesel	1.731	gal	0.222
Natural gas	0.061	cu ft	0.000
Coal		lb	
Electricity	9.123	kWh	0.031
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**0.298**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Alumina Production

Reference Unit:	1 ton of aluminum ingot
Principal Data Source(s):	Aluminum Association - Aluminum Beverage Can LCA
Geographic Location:	North America
Timeframe:	2010
Description:	

Process stage in which alumina is produced by calcining/reacting bauxite with caustic soda and lime.

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	48.095	gal	6.750
Diesel	0.375	gal	0.048
Natural gas	6917.606	cu ft	6.800
Coal	269.207	lb	2.631
Electricity	218.083	kWh	0.744
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**16.973**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Anode Production

Reference Unit: 1 ton of aluminum ingot
Principal Data Source(s): Aluminum Association - Aluminum Beverage Can LCA
Geographic Location: North America
Timeframe: 2010
Description:

Process stage in which anodes are formed by baking coke/pitch for use in electrolysis

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	48.093	gal	0.080
Diesel	0.374	gal	0.015
Natural gas	6917.599	cu ft	0.890
Coal	3.991	lb	0.039
Electricity	218.033	kWh	0.183
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.207**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx	484.510	g	
CH4		g	
N2O		g	
CO2	110862.742	g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Electrolysis

Reference Unit:	1 ton of aluminum ingot
Principal Data Source(s):	Aluminum Association - Aluminum Beverage Can LCA
Geographic Location:	North America
Timeframe:	2010
Description:	

Process stage in which alumina is reduced to form pure aluminum

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	14105.664	kWh	48.133
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**48.133**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx	5443.164	g	
CH4		g	
N2O		g	
CO2	1483564.670	g	

Notes:

CF_4: 62.41 g/ton Al
C_2F_6: 7.45 g/ton Al
Total PFCs: 608,594 g CO_2eq/ton Al (not included CO2 reported above)

Ingot Casting

Reference Unit:	1 ton of aluminum ingot
Principal Data Source(s):	Aluminum Association - Aluminum Beverage Can LCA
Geographic Location:	North America
Timeframe:	2010

Description:

Process stage in which molten aluminum is cast into ingots

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	0.948	gal	0.122
Natural gas	1061.482	cu ft	1.043
Coal	7.162	lb	0.070
Electricity	63.707	kWh	0.217
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.452**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Secondary Production

Reference Unit: 1 ton of aluminum ingot
Principal Data Source(s): Aluminum Association - North American Industry LCA
Geographic Location: North America
Timeframe: 1998
Description:

Process stage for secondary aluminum production, involving the remelt/casting of recycled aluminum. Does not include scrap preparation.

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	4.206	gal	0.590
Diesel	0.044	gal	0.006
Natural gas	1659.175	cu ft	1.631
Coal		lb	
Electricity	191.377	kWh	0.653
Crude Oil		gal	
Distillate Oil		gal	
Gasoline	0.018	gal	0.002
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**2.882**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.
Propane - 1.61E-02 mmBtu (not shown)

Hot Rolling

Reference Unit: 1 ton of rolled aluminum
Principal Data Source(s): Aluminum Association - North American Industry LCA
Geographic Location: North America
Timeframe: 1998
Description:

Process stage for transformation of aluminum ingot to wrought aluminum

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	0.010	gal	0.001
Natural gas	1069.815	cu ft	1.052
Coal		lb	
Electricity	240.355	kWh	0.820
Crude Oil		gal	
Distillate Oil		gal	
Gasoline	0.002	gal	0.000
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.873**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.
Kerosene - 1.72E-04 mmBtu (not shown)
Propane - 6.86E-04 mmBtu (not shown)

Cold Rolling

Reference Unit: 1 ton of rolled aluminum
Principal Data Source(s): Aluminum Association - North American Industry LCA
Geographic Location: North America
Timeframe: 1998
Description:

Process stage for transformation of aluminum ingot to wrought aluminum

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	0.009	gal	0.001
Natural gas	794.354	cu ft	0.781
Coal		lb	
Electricity	316.543	kWh	1.080
Crude Oil		gal	
Distillate Oil		gal	
Gasoline	0.515	gal	0.06
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.922**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.
Propane - 4.80E-03 mmBtu (not shown)

Extrusion

Reference Unit: 1 ton of extruded aluminum
Principal Data Source(s): Aluminum Association - North American Industry LCA
Geographic Location: North America
Timeframe: 1998
Description:

Process stage for transformation of aluminum ingot to extruded aluminum

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	0.001	gal	0.000
Diesel	0.100	gal	0.013
Natural gas	3267.100	cu ft	3.212
Coal	22.408	lb	0.219
Electricity	84.351	kWh	0.288
Crude Oil		gal	
Distillate Oil		gal	
Gasoline	0.011	gal	0.001
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**3.733**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.
Kerosene - 6.83E-04 mmBtu (not shown)
Propane - 9.00E-02 mmBtu (not shown)

Shape Casting

Reference Unit: 1 ton of cast aluminum
Principal Data Source(s): Aluminum Association - North American Industry LCA
Geographic Location: North America
Timeframe: 1998
Description:

Process stage for transformation of aluminum ingot to cast aluminum

MATERIAL PRODUCTION DATA

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	7687.295	cu ft	7.557
Coal		lb	
Electricity	3.655	kWh	0.012
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**7.569**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Comparison of Cast Aluminum Data

	Updated Values	Previously in GREET	Industry Source Aluminum Assoc.
Energy Use (mmBTU/ton)			
Total Energy	115.352	132.856	133.256
Fossil fuels	78.414	96.572	
Coal	50.612	54.477	
Natural gas	19.325	26.210	
Petroleum	8.478	15.885	
Total Emissions(g/ton)			
VOC	637.742	843.946	
CO	1,960.924	2,850.783	
NOx	8,657.103	11,390.999	2,013.540
PM10	20,542.094	30,659.443	8,308.120
PM2.5	8,204.027	13,150.997	
SOx	29,883.924	31,947.068	20,207.960
CH4	10,269.891	12,642.084	
N2O	80.990	99.560	
CO2	8,964,457	8,820,725	
CO2 (VOC, CO, CO2)	8,969,526	8,827,835	
GHGs	9,859,002	9,173,556	10,031,420

Notes:

Industry Values are per ton aluminum ingot, Industry emissions from International Aluminum Institute.

Comparison of Wrought Aluminum Data

	Updated Values	Previously in GREET	Industry Source Aluminum Assoc.
Energy Use (mmBTU/ton)			
Total Energy	164.955	157.507	133.256
Fossil fuels	112.681	119.724	
Coal	75.912	61.487	
Natural gas	24.849	41.381	
Petroleum	11.920	16.855	
Total Emissions(g/ton)			
VOC	924.751	1,018.729	
CO	2,824.190	3,396.301	
NOx	12,502.462	13,428.240	2,013.540
PM10	29,411.160	31,975.284	8,308.120
PM2.5	11,591.450	13,539.925	
SOx	43,049.522	34,351.349	20,207.960
CH4	14,540.617	16,319.137	
N2O	118.043	126.263	
CO2	12,937,641	10,574,404	
CO2 (VOC, CO, CO2)	12,944,961	10,578,253	
GHGs	14,183,513	11,023,858	10,031,420

Notes:

Industry Values are per ton aluminum ingot, Industry emissions from International Aluminum Institute.

Comparison of Extruded Aluminum Data

	Updated Values	Previously in GREET	Industry Source Aluminum Assoc.
Energy Use (mmBTU/ton)			
Total Energy	111.635		133.256
Fossil fuels	74.604		
Coal	51.267		
Natural gas	14.844		
Petroleum	8.493		
Total Emissions(g/ton)			
VOC	613.999		
CO	1,891.841		
NOx	8,415.892		2,013.540
PM10	20,663.393		8,308.120
PM2.5	8,229.564		
SOx	30,014.169		20,207.960
CH4	9,519.356		
N2O	76.862		
CO2	8,767,493		
CO2 (VOC, CO, CO2)	8,772,380		
GHGs	9,641,862		10,031,420

Notes:

Industry Values are per ton aluminum ingot, Industry emissions from International Aluminum Institute.

Nickel Ore Mining

Reference Unit:	1 ton of Class 1 Nickel
Principal Data Source(s):	Nickel Institute LCA
Geographic Location:	North America
Timeframe:	2000.000
Description:	

Process stage in which sulphidic/lateritic ore is extracted from the Earth

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	8.091	gal	1.136
Diesel		gal	
Natural gas	1016.840	cu ft	1.000
Coal		lb	
Electricity	154.809	kWh	0.528
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**2.663**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions.

Nickel Ore Mining (Con't)

PRIMARY ENERGY DATA USED TO ESTIMATE PURCHASED ENERGY DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil			
Diesel			
Natural gas	32.659	kg	1.459
Coal	46.266	kg	0.997
Electricity			
Crude Oil	36.287	kg	1.468
MISC: Uranium	0.0007	kg	0.045
TOTAL			

Notes:

Uranium was not an input into the model, when trying to backcalculate purchased energy.

Beneficiation

Reference Unit: 1 ton of Class 1 Nickel
Principal Data Source(s): Nickel Institute LCA
Geographic Location: North America
Timeframe: 2000.000
Description:

Process stage in which nickel is separated from impurities and other metals contained in the ore, producing nickel concentrate for use in Primary Extraction.

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	6.929	gal	0.972
Diesel		gal	
Natural gas	120.713	cu ft	0.119
Coal		lb	
Electricity	257.173	kWh	0.878
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.969**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions.

Beneficiation (Con't)

PRIMARY ENERGY DATA USED TO ESTIMATE PURCHASED ENERGY DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil			
Diesel			
Natural gas	16.329	kg	0.730
Coal	77.111	kg	1.661
Electricity			
Crude Oil	36.287	kg	1.468
MISC: Uranium	0.0007	kg	0.045
TOTAL			

Notes:

Uranium was not an input into the model, when trying to backcalculate purchased energy.

Primary Extraction

Reference Unit:	1 ton of Class 1 Nickel
Principal Data Source(s):	Nickel Institute LCA
Geographic Location:	North America
Timeframe:	2000.000
Description:	

Process stage in which nickel concentrate is converted into nickel matte via smelting.

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	418.232	gal	58.700
Diesel		gal	
Natural gas	38018.252	cu ft	37.372
Coal		lb	
Electricity	3399.377	kWh	11.600
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**107.672**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions.

Primary Extraction (Con't)

PRIMARY ENERGY DATA USED TO ESTIMATE PURCHASED ENERGY DATA

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil			
Diesel			
Natural gas	1126.723	kg	50.344
Coal	1048.706	kg	22.596
Electricity			
Crude Oil	1687.364	kg	68.268
MISC: Uranium	0.0105	kg	0.716
TOTAL			

Notes:

Uranium was not an input into the model, when trying to backcalculate purchased energy.

Refining

Reference Unit: 1 ton of Class 1 Nickel
Principal Data Source(s): Nickel Institute LCA
Geographic Location: North America
Timeframe: 2000.000
Description:

Process stage in which nickel matte undergoes leaching, separation, and electrolysis to form class I nickel

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	11.790	gal	1.655
Diesel		gal	
Natural gas	16833.062	cu ft	16.547
Coal		lb	
Electricity	1264.825	kWh	4.316
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**22.518**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions.

Refining (Con't)

PRIMARY ENERGY DATA USED TO ESTIMATE PURCHASED ENERGY DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil			
Diesel			
Natural gas	457.221	kg	20.429
Coal	370.131	kg	7.975
Electricity			
Crude Oil	72.575	kg	2.936
MISC: Uranium	0.0212	kg	1.455
TOTAL			

Notes:

Uranium was not an input into the model, when trying to backcalculate purchased energy.

Comparison of Nickel Data

	Updated Values	Previously in GREET	Industry Source Nickel Institute
Energy Use (mmBTU/ton)			
Total Energy	181.208	127.174	181.836
Fossil fuels	179.598	113.634	179.598
Coal	33.229	63.335	33.229
Natural gas	72.962	34.306	72.962
Petroleum	73.407	15.993	73.407
Total Emissions(g/ton)			
VOC	1187.585	917.893	1995.806
CO	3961.952	2760.498	33565.835
NOx	18642.194	11830.619	47173.606
PM10	9967.683	13507.499	35380.205
PM2.5	4283.212	4201.556	
SOx	634678.561	633829.737	878154.828
CH4	22238.973	14859.787	25401.173
N2O	147.424	130.384	1179.340
CO2	13,220,797	10,291,549	12,405,751
CO2 (VOC, CO, CO2)	13,225,287	10,298,747	12,464,718
GHGs	13,825,194	10,709,097	13,451,191

Notes:

Nickel Institute reports PM (unspecified), which is reported as PM10 here.

Ore Mining

Reference Unit: 1 ton of copper
Principal Data Source(s): Fthenakis et al. 2009
Geographic Location: N. American
Timeframe: 1997-2003
Description:

Process stage for copper ore extraction for use in pyrometallurgical processing

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	8.035	gal	1.032
Natural gas		cu ft	
Coal		lb	
Electricity	327.670	kWh	1.118
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**2.150**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Copper Production

Reference Unit: 1 ton of copper
Principal Data Source(s): Fthenakis et al. 2009
Geographic Location: N. American
Timeframe: 1997-2003
Description:

Includes copper smelting and refining activities.

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	10.713	gal	1.376
Natural gas	8749.625	cu ft	8.601
Coal	334.420	lb	3.268
Electricity	1915.607	kWh	6.537
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**19.782**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Wire Drawing

Reference Unit: 1 ton of copper wire
Principal Data Source(s): Sullivan, J. L., Burnham, A., and Wang, M. (2010)
Geographic Location:
Timeframe:
Description:

MATERIAL PRODUCTION DATA

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	5.992	gal	0.841
Diesel		gal	
Natural gas		cu ft	
Coal	2.046	lb	0.020
Electricity	475.336	kWh	1.622
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**2.483**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Comparison of Copper Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	43.299	95.706
Fossil fuels	43.299	90.137
Coal	3.334	26.203
Natural gas	36.309	37.620
Petroleum	3.656	26.314
Total Emissions(g/ton)		
VOC	475.308	666.630
CO	2010.997	2144.665
NOx	4156.742	9624.947
PM10	1174.039	7493.291
PM2.5	532.643	2860.383
SOx	127210.089	195054.269
CH4	6942.755	12162.939
N2O	57.020	88.318
CO2	2,838,004	7,355,950
CO2 (VOC, CO, CO2)	2,840,283	7,361,398
GHGs	3,030,844	7,691,790

Notes:

No Current Industry Sources
Updated Values include transformation into copper wire, this does not appear to be included in previous GREET

Acrylonitrile-Butadiene-Styrene Production

Reference Unit:	1 ton of ABS Resin
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	1970's, 1992, 2003-2004

Description:

Cradle to resin inventory for production of acrylonitrile-butadiene-styrene (ABS) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	8.620	gal	1.210
Diesel	0.006	gal	0.001
Natural gas	18074.000	cu ft	17.767
Coal	136.800	lb	1.337
Electricity	1010.000	kWh	3.446
Crude Oil		gal	
Distillate Oil	0.820	gal	0.105
Gasoline	0.220	gal	0.026
LPG	0.180	gal	0.015
MISC: Process off-gas from Oil	106.400	lb	2.966
MISC: Process off-gas from NG	200.000	lb	5.682
MISC: Recovered Energy		x	-0.414
TOTAL			**32.555**
Feedstock Inputs	Value	Unit	
Crude Oil	172.947	gal	22.426
Natural Gas	22309.278	cu ft	21.930
TOTAL			**44.356**
Non-combustion Emissions	Value	Unit	
VOC	453.592	g	
CO	8327.956	g	
NOx	816.466	g	
PM10	67.132	g	
PM2.5	4.808	g	
SOx	15422.141	g	
CH4	10160.469	g	
N2O	0.000	g	
CO2	235868.032	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 2% of the the total fuel input.

Acrylonitrile-Butadiene-Styrene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	115.8	1.22	gal	0.157
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	254	0.62	gal	0.080
Barge (Diesel)	828	0.66	gal	0.085
Barge (Resid. Oil)		2.2	gal	0.309
Ocean Freighter (Diesel)	2276	0.44	gal	0.057
Ocean Freighter (Resid. Oil)		3.9	gal	0.547
NG Pipeline (NG)	626	432	cu ft	0.425
Petro Pipeline (Electricity)	446	9.7	kWh	0.033
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**1.6915**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	14.720	gal	2.066
Diesel	2.946	gal	0.378
Natural gas	18506.000	cu ft	18.191
Coal	136.800	lb	1.337
Electricity	1019.700	kWh	3.479
Crude Oil		gal	
Distillate Oil	0.820	gal	0.105
Gasoline	0.220	gal	0.026
LPG	0.180	gal	0.015
MISC: Process off-gas from Oil	106.400	lb	2.966
MISC: Process off-gas from NG	200.000	lb	5.682
MISC: Recovered Energy		x	-0.414
TOTAL			**34.246**

Notes:

Comparison of ABS Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	83.801	–	91.44
Fossil fuels	82.592	–	
Coal	6.997	–	
Natural gas	48.467	–	
Petroleum	27.128	–	
Total Emissions(g/ton)			
VOC	676.452	–	1157.427
CO	9196.307	–	13558.429
NOx	3586.311	–	8465.751
PM10	1560.829	–	485.017
PM2.5	489.655	–	5.842
SOx	17957.286	–	19621.141
CH4	14962.518	–	21935.995
N2O	33.223	–	78.264
CO2	2,753,184	–	3,550,765
CO2 (VOC, CO, CO2)	2,769,744	–	3,576,002
GHGs	3,153,707	–	4,107,212

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Ethylene Propylene Diene Monomer Production

Reference Unit: 1 ton of EPDM Resin
Principal Data Source(s): Athena Institute, Plastics Division of the ACC
Geographic Location: North America
Timeframe: 2003
Description:

Cradle to gate inventory for ethylene propylene diene monomer (EPDM) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	2.117	gal	0.297
Diesel	0.014	gal	0.002
Natural gas	6494.039	cu ft	6.384
Coal	0.000	lb	0.000
Electricity	181.624	kWh	0.620
Crude Oil		gal	
Distillate Oil	0.372	gal	0.048
Gasoline	0.224	gal	0.026
LPG	0.080	gal	0.007
MISC: Process off-gas from Oil	81.348	lb	2.383
MISC: Process off-gas from NG	239.650	lb	7.141
MISC: Recovered Energy		x	-0.018
TOTAL			**16.907**
Feedstock Inputs	Value	Unit	
Crude Oil	86.668	gal	11.238
Natural Gas	38949.142	cu ft	38.287
TOTAL			**49.525**
Non-combustion Emissions	Value	Unit	
VOC	627.381	g	
CO	3452.942	g	
NOx	85.652	g	
PM10	90.718	g	
PM2.5	0.000	g	
SOx	20126.427	g	
CH4	12299.587	g	
N2O	0.000	g	
CO2	65708.430	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.
Based on an Athena Institute report done by Franklin Associates in 2001 we used unit processes for 1306lbs ethylene, 616lbs propylene, and 78lbs butadiene to model EPDM.

Ethylene Propylene Diene Monomer Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	24.06	1.08	gal	0.139
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	21.25	0.05	gal	0.007
Barge (Diesel)	42.39	0.03	gal	0.004
Barge (Resid. Oil)		0.12	gal	0.016
Ocean Freighter (Diesel)	870.94	0.17	gal	0.021
Ocean Freighter (Resid. Oil)		1.49	gal	0.209
NG Pipeline (NG)	885.15	610.76	cu ft	0.600
Petro Pipeline (Electricity)	271.09	5.92	kWh	0.020
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**1.017**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	3.723	gal	0.523
Diesel	1.344	gal	0.173
Natural gas	7104.796	cu ft	6.984
Coal	0.000	lb	0.000
Electricity	187.539	kWh	0.640
Crude Oil		gal	
Distillate Oil	0.372	gal	0.048
Gasoline	0.224	gal	0.026
LPG	0.080	gal	0.007
MISC: Process off-gas from Oil	81.348	lb	2.383
MISC: Process off-gas from NG	239.650	lb	7.141
MISC: Recovered Energy		x	-0.018
TOTAL			**17.924**

Notes:

Comparison of EPDM Data

	Updated Values	Previously in GREET	Industry Source None
Energy Use (mmBTU/ton)			
Total Energy	67.918	–	–
Fossil fuels	67.699	–	–
Coal	1.027	–	–
Natural gas	52.655	–	–
Petroleum	14.017	–	–
Total Emissions(g/ton)			
VOC	693.878	–	–
CO	3709.203	–	–
NOx	763.261	–	–
PM10	306.210	–	–
PM2.5	67.445	–	–
SOx	20605.933	–	–
CH4	13776.766	–	–
N2O	9.880	–	–
CO2	1011176.419	–	–
CO2 (VOC, CO, CO2)	1019167.752	–	–
GHGs	1366531.277	–	–

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Liquid Epoxy Production

Reference Unit: 1 ton of Liquid Epoxy Resin
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 1994-2001
Description:

Cradle to resin inventory for production of liquid epoxy resin.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	43460.573	cu ft	42.722
Coal		lb	
Electricity	1917.929	kWh	6.544
Crude Oil	72.484	gal	9.399
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**58.665**
Feedstock Inputs	Value	Unit	
Crude Oil	96.386	gal	12.498
Natural Gas	21635.529	cu ft	21.268
TOTAL			**33.766**
Non-combustion Emissions	Value	Unit	
VOC	7.678	g	
CO	356.616	g	
NOx	794.395	g	
PM10	6175.304	g	
PM2.5		g	
SOx	596.721	g	
CH4	1593.406	g	
N2O	0.003	g	
CO2	293928.2	g	

Notes:

Energy content calculated using GREET heating value assumptions.

Liquid Epoxy Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.863	gal	0.242
Natural Gas		82.811	cu ft	0.081
Electricity		123.340	kWh	0.421
TOTAL				**0.744**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	43543.384	cu ft	42.803
Coal		lb	
Electricity	2041.269	kWh	6.965
Crude Oil	74.347	gal	9.641
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**59.409**

Notes:

Upstream energy included in the European portion of transportation data was removed by applying the delivered fuel energy to total energy ratio for each fuel. This ratio was unique to each data set.

Comparison of Epoxy Data

	Updated Values	Previously in GREET	Industry Source PlasticsEurope	Industry Source Source #2
Energy Use (mmBTU/ton)				
Total Energy	106.283	–	117.885	
Fossil fuels	103.974	–	106.534	
Coal	10.787	–	10.653	
Natural gas	70.596	–	70.292	
Petroleum	22.591	–	25.585	
Total Emissions(g/ton)				
VOC	487.823	–	7.777	
CO	2042.538	–	4259.720	
NOx	7638.815	–	12169.988	
PM10	8529.681	–	7833.753	
PM2.5	844.060	–		
SOx	8130.174	–	10805.578	
CH4	12785.464	–	92198.337	
N2O	88.696	–	0.003	
CO2	5,222,053	–	5,178,627	
CO2 (VOC, CO, CO2)	5,226,783	–	5,185,435	
GHGs	5,572,851	–	7,317,902	

Notes:

Energy data from PlasticsEurope is in terms of HHV.
Recovered energy (6.994 mmBtu/ton) was incorporated into the natural gas, fossil fuels, and total energy calculations.

General-Purpose Polystyrene Production

Reference Unit: 1 ton of GPPS Resin
Principal Data Source(s): Plastics Division of the ACC
Geographic Location: North America
Timeframe: 1992-1993, 2002-2003
Description:

Cradle to gate inventory for general-purpose polystyrene (GPPS) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	11.160	gal	1.566
Diesel	0.007	gal	0.001
Natural gas	19752.000	cu ft	19.416
Coal	0.000	lb	0.000
Electricity	462.000	kWh	1.576
Crude Oil		gal	
Distillate Oil	1.000	gal	0.128
Gasoline	0.220	gal	0.026
LPG	0.200	gal	0.017
MISC: Process off-gas from Oil	79.800	lb	2.210
MISC: Process off-gas from NG	158.600	lb	4.538
MISC: Recovered Energy		x	-0.008
TOTAL			**29.479**
Feedstock Inputs	Value	Unit	
Crude Oil	201.536	gal	26.133
Natural Gas	16783.505	cu ft	16.498
TOTAL			**42.631**
Non-combustion Emissions	Value	Unit	
VOC	344.730	g	
CO	9062.776	g	
NOx	390.089	g	
PM10	50.802	g	
PM2.5	7.076	g	
SOx	12337.712	g	
CH4	8545.680	g	
N2O	0.000	g	
CO2	303906.888	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

General-Purpose Polystyrene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)	176.8	1.86	gal	0.239
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	284	0.7	gal	0.090
Barge (Diesel)	850	0.68	gal	0.087
Barge (Resid. Oil)		2.26	gal	0.317
Ocean Freighter (Diesel)	2374	0.46	gal	0.059
Ocean Freighter (Resid. Oil)		4.06	gal	0.570
NG Pipeline (NG)	476	328	cu ft	0.322
Petro Pipeline (Electricity)	488	10.64	kWh	0.036
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**1.721**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil	17.480	gal	2.453
Diesel	3.707	gal	0.476
Natural gas	20080.000	cu ft	19.739
Coal	0.000	lb	0.000
Electricity	472.640	kWh	1.613
Crude Oil		gal	
Distillate Oil	1.000	gal	0.128
Gasoline	0.220	gal	0.026
LPG	0.200	gal	0.017
MISC: Process off-gas from Oil	79.800	lb	2.210
MISC: Process off-gas from NG	158.600	lb	4.538
MISC: Recovered Energy		x	-0.008
TOTAL			**31.200**

Notes:

Comparison of GPPS Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	76.221	–	82.668
Fossil fuels	75.659	–	
Coal	2.640	–	
Natural gas	42.665	–	
Petroleum	30.354	–	
Total Emissions(g/ton)			
VOC	534.047	–	1058.219
CO	9737.139	–	14219.816
NOx	2598.084	–	6514.660
PM10	672.173	–	286.601
PM2.5	246.378	–	8.598
SOx	13718.710	–	16093.745
CH4	13014.442	–	19290.448
N2O	28.755	–	41.888
CO2	2,288,062	–	2,993,878
CO2 (VOC, CO, CO2)	2,305,028	–	3,019,855
GHGs	2,638,958	–	3,494,327

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

High-Impact Polystyrene Production

Reference Unit: 1 ton of HIPS Resin
Principal Data Source(s): Plastics Division of the ACC
Geographic Location: North America
Timeframe: 1970's, 1992-1993, 2000-2003
Description:

Cradle to gate inventory for high-impact polystyrene (HIPS) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	11.440	gal	1.606
Diesel	0.007	gal	0.001
Natural gas	19384.000	cu ft	19.054
Coal	0.000	lb	0.000
Electricity	470.000	kWh	1.604
Crude Oil		gal	
Distillate Oil	0.980	gal	0.126
Gasoline	0.220	gal	0.026
LPG	0.240	gal	0.020
MISC: Process off-gas from Oil	85.400	lb	2.368
MISC: Process off-gas from NG	167.800	lb	4.780
MISC: Recovered Energy		x	-0.008
TOTAL			**29.584**
Feedstock Inputs	Value	Unit	
Crude Oil	200.121	gal	25.950
Natural Gas	17525.773	cu ft	17.228
TOTAL			**43.177**
Non-combustion Emissions	Value	Unit	
VOC	362.874	g	
CO	9017.416	g	
NOx	381.018	g	
PM10	62.596	g	
PM2.5	6.622	g	
SOx	12791.305	g	
CH4	8817.836	g	
N2O	0.000	g	
CO2	288484.747	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

High-Impact Polystyrene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	176.8	1.86	gal	0.239
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	284	0.7	gal	0.090
Barge (Diesel)	850	0.68	gal	0.087
Barge (Resid. Oil)		2.26	gal	0.317
Ocean Freighter (Diesel)	2374	0.46	gal	0.059
Ocean Freighter (Resid. Oil)		4.06	gal	0.570
NG Pipeline (NG)	476	328	cu ft	0.322
Petro Pipeline (Electricity)	488	10.64	kWh	0.036
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**1.721**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	17.760	gal	2.493
Diesel	3.707	gal	0.476
Natural gas	19712.000	cu ft	19.377
Coal	0.000	lb	0.000
Electricity	480.640	kWh	1.640
Crude Oil		gal	
Distillate Oil	0.980	gal	0.126
Gasoline	0.220	gal	0.026
LPG	0.240	gal	0.020
MISC: Process off-gas from Oil	85.400	lb	2.368
MISC: Process off-gas from NG	167.800	lb	4.780
MISC: Recovered Energy		x	-0.008
TOTAL			**31.305**

Notes:

Comparison of HIPS Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	76.892	–	83.44
Fossil fuels	76.321	–	
Coal	2.683	–	
Natural gas	43.271	–	
Petroleum	30.368	–	
Total Emissions(g/ton)			
VOC	549.841	–	1069.242
CO	9669.043	–	14219.816
NOx	2578.898	–	6602.845
PM10	683.432	–	297.624
PM2.5	243.984	–	8.047
SOx	14200.043	–	16644.901
CH4	13223.193	–	19510.910
N2O	28.044	–	41.888
CO2	2,277,184	–	3,013,146
CO2 (VOC, CO, CO2)	2,294,091	–	3,039,158
GHGs	2,633,028	–	3,508,657

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

High-Density Polyethylene Production

Reference Unit: 1 ton of HDPE Resin
Principal Data Source(s): Plastics Division of the ACC
Geographic Location: North America
Timeframe: 2003
Description:

Cradle to resin inventory for high-density polyethylene (HDPE) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	3.040	gal	0.427
Diesel	0.019	gal	0.002
Natural gas	9720.000	cu ft	9.555
Coal	0.000	lb	0.000
Electricity	320.000	kWh	1.092
Crude Oil		gal	
Distillate Oil	0.360	gal	0.046
Gasoline	0.220	gal	0.026
LPG	0.068	gal	0.006
MISC: Process off-gas from Oil	51.600	lb	1.584
MISC: Process off-gas from NG	236.000	lb	7.216
MISC: Recovered Energy		x	-0.024
TOTAL			**19.953**
Feedstock Inputs	Value	Unit	
Crude Oil	54.064	gal	7.010
Natural Gas	34845.361	cu ft	34.253
TOTAL			**41.263**
Non-combustion Emissions	Value	Unit	
VOC	662.245	g	
CO	2685.267	g	
NOx	88.904	g	
PM10	127.006	g	
PM2.5	10.886	g	
SOx	21137.404	g	
CH4	12791.305	g	
N2O	0.000	g	
CO2	69762.507	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

High-Density Polyethylene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)	15.12	0.16	gal	0.020
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	13.06	0.03	gal	0.004
Barge (Diesel)	31.20	0.03	gal	0.003
Barge (Resid. Oil)		0.09	gal	0.012
Ocean Freighter (Diesel)	640.00	0.12	gal	0.016
Ocean Freighter (Resid. Oil)		1.10	gal	0.154
NG Pipeline (NG)	940.00	648.00	cu ft	0.637
Petro Pipeline (Electricity)	248.00	5.42	kWh	0.018
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**0.866**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil	4.226	gal	0.593
Diesel	0.359	gal	0.046
Natural gas	10368.000	cu ft	10.192
Coal	0.000	lb	0.000
Electricity	325.420	kWh	1.110
Crude Oil		gal	
Distillate Oil	0.360	gal	0.046
Gasoline	0.220	gal	0.026
LPG	0.068	gal	0.006
MISC: Process off-gas from Oil	51.600	lb	1.584
MISC: Process off-gas from NG	236.000	lb	7.216
MISC: Recovered Energy		x	-0.024
TOTAL			**20.819**

Notes:

Comparison of HDPE Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	63.688	45.977	70.46
Fossil fuels	63.303	43.646	
Coal	1.803	10.994	
Natural gas	52.263	18.320	
Petroleum	9.237	14.332	
Total Emissions(g/ton)			
VOC	762.237	499.746	1069.242
CO	2970.417	1035.969	4596.638
NOx	1001.694	4725.855	2590.432
PM10	496.474	2622.888	242.508
PM2.5	128.645	965.636	13.228
SOx	21894.170	6344.230	26124.778
CH4	15043.573	5853.654	19510.910
N2O	15.197	41.271	19.842
CO2	1,289,195	3,521,214	1,511,114
CO2 (VOC, CO, CO2)	1,296,238	3,522,388	1,521,801
GHGs	1,676,856	3,681,028	1,999,593

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Low Density Polyethylene Production

Reference Unit:	1 ton of LDPE Resin
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	2002-2003
Description:	

Cradle to resin inventory of low density polyethylene (LDPE) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	1.960	gal	0.275
Diesel	0.020	gal	0.003
Natural gas	13284.000	cu ft	13.058
Coal	0.000	lb	0.000
Electricity	332.000	kWh	1.133
Crude Oil		gal	
Distillate Oil	0.380	gal	0.049
Gasoline	0.240	gal	0.028
LPG	0.068	gal	0.006
MISC: Process off-gas from Oil	52.600	lb	1.614
MISC: Process off-gas from NG	240.000	lb	7.348
MISC: Recovered Energy		x	-0.366
TOTAL			**23.238**
Feedstock Inputs	Value	Unit	
Crude Oil	54.913	gal	7.121
Natural Gas	35505.155	cu ft	34.902
TOTAL			**42.022**
Non-combustion Emissions	Value	Unit	
VOC	680.389	g	
CO	2685.267	g	
NOx	65.317	g	
PM10	117.934	g	
PM2.5	4.990	g	
SOx	21590.997	g	
CH4	12972.742	g	
N2O	0.907	g	
CO2	80104.413	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 2% of total fuel inputs.

Low Density Polyethylene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)	15.38	0.162	gal	0.021
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	13.3	0.032	gal	0.004
Barge (Diesel)	31.6	0.026	gal	0.003
Barge (Resid. Oil)		0.084	gal	0.012
Ocean Freighter (Diesel)	652	0.134	gal	0.017
Ocean Freighter (Resid. Oil)		1.14	gal	0.160
NG Pipeline (NG)	956	660	cu ft	0.649
Petro Pipeline (Electricity)	254	5.52	kWh	0.019
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**0.885**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil	3.184	gal	0.447
Diesel	0.374	gal	0.048
Natural gas	13944.000	cu ft	13.707
Coal	0.000	lb	0.000
Electricity	337.520	kWh	1.152
Crude Oil		gal	
Distillate Oil	0.380	gal	0.049
Gasoline	0.240	gal	0.028
LPG	0.068	gal	0.006
MISC: Process off-gas from Oil	52.600	lb	1.614
MISC: Process off-gas from NG	240.000	lb	7.348
MISC: Recovered Energy		x	-0.366
TOTAL			**24.398**

Notes:

Comparison of LDPE Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	68.309	–	75.064
Fossil fuels	67.908	–	
Coal	1.877	–	
Natural gas	56.795	–	
Petroleum	9.237	–	
Total Emissions(g/ton)			
VOC	806.224	–	1091.288
CO	3055.837	–	4464.361
NOx	1244.186	–	2590.432
PM10	506.331	–	231.485
PM2.5	134.102	–	6.063
SOx	22375.847	–	26565.703
CH4	15913.840	–	20062.066
N2O	20.406	–	22.046
CO2	1,526,400	–	1,564,224
CO2 (VOC, CO, CO2)	1,533,715	–	1,574,769
GHGs	1,937,642	–	2,067,936

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Linear-Low Density Polyethylene Production

Reference Unit:	1 ton of LLDPE Resin
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	2003
Description:	

Cradle to resin inventory of linear-low density polyethylene (LLDPE) production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	2.420	gal	0.340
Diesel	0.020	gal	0.003
Natural gas	9592.000	cu ft	9.429
Coal	0.000	lb	0.000
Electricity	274.000	kWh	0.935
Crude Oil		gal	
Distillate Oil	0.360	gal	0.046
Gasoline	0.240	gal	0.028
LPG	0.060	gal	0.005
MISC: Process off-gas from Oil	52.200	lb	1.600
MISC: Process off-gas from NG	238.000	lb	7.284
MISC: Recovered Energy		x	-0.024
TOTAL			**19.669**
Feedstock Inputs	Value	Unit	
Crude Oil	54.347	gal	7.047
Natural Gas	35175.258	cu ft	34.577
TOTAL			**41.624**
Non-combustion Emissions	Value	Unit	
VOC	671.317	g	
CO	2648.979	g	
NOx	90.718	g	
PM10	99.790	g	
PM2.5	9.072	g	
SOx	21409.560	g	
CH4	12882.023	g	
N2O	15.422	g	
CO2	116119.647	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

Linear-Low Density Polyethylene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	15.26	0.16	gal	0.021
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	13.18	0.032	gal	0.004
Barge (Diesel)	31.4	0.026	gal	0.003
Barge (Resid. Oil)		0.084	gal	0.012
Ocean Freighter (Diesel)	646	0.134	gal	0.017
Ocean Freighter (Resid. Oil)		1.1	gal	0.154
NG Pipeline (NG)	948	654	cu ft	0.643
Petro Pipeline (Electricity)	252	5.48	kWh	0.019
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**0.873**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	3.604	gal	0.506
Diesel	0.372	gal	0.048
Natural gas	10246.000	cu ft	10.072
Coal	0.000	lb	0.000
Electricity	279.480	kWh	0.954
Crude Oil		gal	
Distillate Oil	0.360	gal	0.046
Gasoline	0.240	gal	0.028
LPG	0.060	gal	0.005
MISC: Process off-gas from Oil	52.200	lb	1.600
MISC: Process off-gas from NG	238.000	lb	7.284
MISC: Recovered Energy		x	-0.024
TOTAL			**20.542**

Notes:

Comparison of LLDPE Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	63.500	–	70.256
Fossil fuels	63.169	–	
Coal	1.547	–	
Natural gas	52.433	–	
Petroleum	9.190	–	
Total Emissions(g/ton)			
VOC	767.095	–	1080.265
CO	3014.566	–	4519.476
NOx	1771.366	–	2480.200
PM10	426.794	–	209.439
PM2.5	111.877	–	11.023
SOx	22381.806	–	26345.240
CH4	15055.686	–	19731.372
N2O	30.070	–	38.581
CO2	2,395,936	–	1,541,263
CO2 (VOC, CO, CO2)	2,403,064	–	1,551,861
GHGs	2,788,417	–	2,040,378

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Nylon 6 Production

Reference Unit:	1 ton of Nylon 6 Production
Principal Data Source(s):	PlasticsEurope
Geographic Location:	Europe
Timeframe:	1994, 1999-2002, 2007
Description:	

Cradle to resin inventory for nylon 6 resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	34768.407	cu ft	34.177
Coal		lb	
Electricity	1163.803	kWh	3.971
Crude Oil	108.571	gal	14.078
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**52.22678**
Feedstock Inputs	Value	Unit	
Crude Oil	115.138	gal	14.930
Natural Gas	15872.359	cu ft	15.603
TOTAL			**30.532**
Non-combustion Emissions	Value	Unit	
VOC	18.435	g	
CO	5050.056	g	
NOx	7470.088	g	
PM10	156.335	g	
PM2.5		g	
SOx	440.054	g	
CH4	2246.827	g	
N2O	7809.833	g	
CO2	1043225.845	g	

Notes:

Energy content calculated using GREET heating value assumptions.

Nylon 6 Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		4.282	gal	0.555
Natural Gas		110.154	cu ft	0.108
Electricity		98.460	kWh	0.336
TOTAL				**0.999**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	34878.561	cu ft	34.286
Coal		lb	
Electricity	1262.262	kWh	4.307
Crude Oil	112.853	gal	14.634
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**53.226**

Notes:

Upstream energy included in the European portion of transportation data was removed by applying the delivered fuel energy to total energy ratio for each fuel. This ratio was unique to each data set.

Comparison of Nylon 6 Data

	Updated Values	Previously in GREET	Industry Source PlasticsEurope
Energy Use (mmBTU/ton)			
Total Energy	92.208	–	103.588
Fossil fuels	90.790	–	95.784
Coal	6.626	–	11.939
Natural gas	54.597	–	50.679
Petroleum	29.566	–	33.165
Total Emissions(g/ton)			
VOC	407.128	–	18.481
CO	6528.715	–	8836.469
NOx	14014.264	–	16866.847
PM10	1884.136	–	2640.409
PM2.5	712.631	–	
SOx	8489.632	–	15058.231
CH4	11448.642	–	42518.689
N2O	7890.922	–	7809.753
CO2	5,255,372	–	4,954,035
CO2 (VOC, CO, CO2)	5,266,901	–	4,968,166
GHGs	7,904,612	–	8,280,100

Notes:

Energy data from PlasticsEurope is in terms of HHV.

Recovered energy (10.151 mmBtu/ton) was incorporated into the natural gas, fossil fuels, and total energy calculations.

Nylon 66 Production

Reference Unit: 1 ton of Nylon 66 Resin
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 1996-2002
Description:

Cradle to resin inventory for nylon 66 resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	33284.536	cu ft	32.719
Coal		lb	
Electricity	2037.778	kWh	6.953
Crude Oil	88.719	gal	11.504
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**51.176**
Feedstock Inputs	Value	Unit	
Crude Oil	155.636	gal	20.181
Natural Gas	20239.657	cu ft	19.896
TOTAL			**40.077**
Non-combustion Emissions	Value	Unit	
VOC	19.612	g	
CO	1565.294	g	
NOx	1620.850	g	
PM10	211.424	g	
PM2.5		g	
SOx	402.330	g	
CH4	2024.299	g	
N2O	662.083	g	
CO2	835981.451	g	

Notes:

Energy content calculated using GREET heating value assumptions.

Nylon 66 Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.704	gal	0.221
Natural Gas		137.158	cu ft	0.135
Electricity		127.034	kWh	0.433
TOTAL				**0.789**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	33421.694	cu ft	32.854
Coal		lb	
Electricity	2164.812	kWh	7.387
Crude Oil	90.424	gal	11.725
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**51.965**

Notes:

Upstream energy included in the European portion of transportation data was removed by applying the delivered fuel energy to total energy ratio for each fuel. This ratio was unique to each data set.

Comparison of Nylon 66 Data

	Updated Values	Previously in GREET	Industry Source PlasticsEurope
Energy Use (mmBTU/ton)			
Total Energy	105.129	–	119.202
Fossil fuels	102.680	–	110.167
Coal	11.440	–	15.903
Natural gas	58.848	–	58.513
Petroleum	32.391	–	35.749
Total Emissions(g/ton)			
VOC	442.774	–	19.675
CO	3093.002	–	6637.763
NOx	8186.669	–	12280.543
PM10	2709.107	–	1931.106
PM2.5	880.287	–	
SOx	8869.070	–	16161.913
CH4	11554.776	–	44688.010
N2O	744.446	–	668.100
CO2	5,377,578	–	5,934,498
CO2 (VOC, CO, CO2)	5,383,818	–	5,945,131
GHGs	5,894,533	–	7,184,794

Notes:

Energy data from PlasticsEurope is in terms of HHV.
Recovered energy (4.248 mmBtu/ton) was incorporated into the natural gas, fossil fuels, and total energy calculations.

Polycarbonate Production

Reference Unit:	1 ton of PC Resin
Principal Data Source(s):	PlasticsEurope
Geographic Location:	Europe
Timeframe:	1994, 1999-2002, 2007
Description:	

Cradle to resin inventory for polycarbonate (PC).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	28412.870	cu ft	27.930
Coal	0.020	lb	0.400
Electricity	1679.339	kWh	5.730
Crude Oil	65.564	gal	8.502
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**42.562**
Feedstock Inputs	Value	Unit	
Crude Oil	189.568	gal	24.581
Natural Gas	4737.690	cu ft	4.657
TOTAL			**29.238**
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Physical Units for fuel inputs calculated using GREET heating value assumptions. Results were calculated from total primary energy data using assumptions in GREET 1.8c model.

Non-combustion emissions were not reported separately

Polycarbonate Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity		kWh	
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			

Notes:

Transport was not calculated for PC as it was estimated to be less than 2% of total energy input.

Comparison of PC Data

	Updated Values	Previously in GREET	Industry Source PlasticsEurope
Energy Use (mmBTU/ton)			
Total Energy	83.263	–	89.935
Fossil fuels	81.245	–	83.349
Coal	9.827	–	5.890
Natural gas	37.761	–	38.351
Petroleum	33.658	–	36.451
Total Emissions(g/ton)			
VOC	355.523	–	2275.052
CO	1284.459	–	1451.496
NOx	5354.616	–	4508.708
PM10	2139.440	–	27.488
PM2.5	746.170	–	90.718
SOx	6676.477	–	3710.386
CH4	8003.297	–	10953.294
N2O	67.393	–	79.288
CO2	3,768,919	–	3,456,374
CO2 (VOC, CO, CO2)	3,772,046	–	3,465,848
GHGs	3,992,211	–	3,746,673

Notes:

Energy data from PlasticsEurope is in terms of HHV.

Polyester Terephthalate Production

Reference Unit:	1 ton of PET Resin
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	1990-1994, 2001-2004
Description:	

Cradle to resin inventory for polyester terephthalate (PET) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	19.200	gal	2.695
Diesel	0.004	gal	0.000
Natural gas	11684.000	cu ft	11.485
Coal	71.800	lb	0.702
Electricity	800.000	kWh	2.730
Crude Oil		gal	
Distillate Oil	3.320	gal	0.426
Gasoline	0.142	gal	0.016
LPG	1.360	gal	0.116
MISC: Process off-gas from Oil	10.440	lb	0.320
MISC: Process off-gas from NG	47.600	lb	1.458
MISC: Recovered Energy		x	-0.127
TOTAL			**19.948**
Feedstock Inputs	Value	Unit	
Crude Oil	163.323	gal	21.178
Natural Gas	9030.928	cu ft	8.877
TOTAL			**30.056**
Non-combustion Emissions	Value	Unit	
VOC	163.293	g	
CO	12065.557	g	
NOx	217.724	g	
PM10	18.144	g	
PM2.5	0.000	g	
SOx	6431.940	g	
CH4	5787.839	g	
N2O	0.000	g	
CO2	268526.683	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

Polyester Terephthalate Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	17.7	0.186	gal	0.024
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	1014	2.52	gal	0.324
Barge (Diesel)	86.2	0.068	gal	0.009
Barge (Resid. Oil)		0.22	gal	0.031
Ocean Freighter (Diesel)	1716	0.32	gal	0.041
Ocean Freighter (Resid. Oil)		2.94	gal	0.413
NG Pipeline (NG)	238	163.8	cu ft	0.161
Petro Pipeline (Electricity)	374	8.14	kWh	0.028
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**1.030**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	22.360	gal	3.138
Diesel	3.098	gal	0.398
Natural gas	11847.800	cu ft	11.646
Coal	71.800	lb	0.702
Electricity	808.140	kWh	2.757
Crude Oil		gal	
Distillate Oil	3.320	gal	0.426
Gasoline	0.142	gal	0.016
LPG	1.360	gal	0.116
MISC: Process off-gas from Oil	10.440	lb	0.320
MISC: Process off-gas from NG	47.600	lb	1.458
MISC: Recovered Energy		x	-0.127
TOTAL			**20.978**

Notes:

Comparison of PET Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	55.563	74.537	60.814
Fossil fuels	54.601	72.927	
Coal	5.225	7.892	
Natural gas	24.223	16.531	
Petroleum	25.153	48.503	
Total Emissions(g/ton)			
VOC	334.495	676.980	639.341
CO	12667.965	1730.703	18077.905
NOx	2367.272	9429.901	6657.960
PM10	1192.370	3585.871	319.670
PM2.5	404.794	1804.166	0.000
SOx	8673.291	12421.151	9060.999
CH4	9264.640	8101.291	13778.891
N2O	28.895	49.668	52.911
CO2	2,053,513	6,011,201	2,586,243
CO2 (VOC, CO, CO2)	2,074,463	6,013,162	2,617,046
GHGs	2,314,689	6,230,495	2,932,148

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Polypropylene Production

Reference Unit:	1 ton of Polypropylene Resin
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	2003-2004

Description:

Cradle to resin inventory for polypropylene (PP) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	4.060	gal	0.570
Diesel	0.004	gal	0.000
Natural gas	7584.000	cu ft	7.455
Coal	0.000	lb	0.000
Electricity	354.000	kWh	1.208
Crude Oil		gal	
Distillate Oil	0.380	gal	0.049
Gasoline	0.220	gal	0.026
LPG	0.120	gal	0.010
MISC: Process off-gas from Oil	132.000	lb	3.754
MISC: Process off-gas from NG	234.000	lb	6.672
MISC: Recovered Energy		x	-0.005
TOTAL			**19.744**
Feedstock Inputs	Value	Unit	
Crude Oil	105.580	gal	13.691
Natural Gas	27134.021	cu ft	26.673
TOTAL			**40.363**
Non-combustion Emissions	Value	Unit	
VOC	535.239	g	
CO	5252.600	g	
NOx	136.078	g	
PM10	90.718	g	
PM2.5	0.009	g	
SOx	17599.384	g	
CH4	11158.372	g	
N2O	4.082	g	
CO2	73754.119	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

Polypropylene Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)	19.18	0.2	gal	0.026
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	15	0.038	gal	0.005
Barge (Diesel)	63.2	0.05	gal	0.006
Barge (Resid. Oil)		0.168	gal	0.024
Ocean Freighter (Diesel)	1298	0.24	gal	0.031
Ocean Freighter (Resid. Oil)		2.2	gal	0.309
NG Pipeline (NG)	758	522	cu ft	0.513
Petro Pipeline (Electricity)	304	6.6	kWh	0.023
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**0.936**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil	6.428	gal	0.902
Diesel	0.532	gal	0.068
Natural gas	8106.000	cu ft	7.968
Coal	0.000	lb	0.000
Electricity	360.600	kWh	1.230
Crude Oil		gal	
Distillate Oil	0.380	gal	0.049
Gasoline	0.220	gal	0.026
LPG	0.120	gal	0.010
MISC: Process off-gas from Oil	132.000	lb	3.754
MISC: Process off-gas from NG	234.000	lb	6.672
MISC: Recovered Energy		x	-0.005
TOTAL			**20.680**

Notes:

Comparison of PP Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	62.628	42.063	68.676
Fossil fuels	62.204	39.468	
Coal	1.990	12.204	
Natural gas	41.972	15.724	
Petroleum	18.242	11.541	
Total Emissions(g/ton)			
VOC	627.027	475.145	892.872
CO	5759.420	940.900	7804.364
NOx	1358.622	4240.351	3130.564
PM10	496.921	2702.166	209.439
PM2.5	127.778	930.593	0.011
SOx	18477.988	6102.322	21935.995
CH4	13044.833	5271.525	17085.825
N2O	16.624	38.835	24.251
CO2	1,272,575	3,256,624	1,551,316
CO2 (VOC, CO, CO2)	1,283,580	3,257,690	1,566,556
GHGs	1,614,654	3,401,051	1,980,853

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Flexible Polyurethane Foam Production

Reference Unit: 1 ton of Flexible Polyurethane Foam
Principal Data Source(s): Plastics Division of the ACC and PlasticsEurope
Geographic Location: North America and Europe
Timeframe: 1990-1993, 1996, 2003-2005
Description:

Inventory of cradle to semi-finished product for flexible polyurethane (PUR) foam. Data for precursors is North American. Data for foam production is calculated from European data.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	22.627	gal	3.176
Diesel	0.214	gal	0.027
Natural gas	18339.139	cu ft	18.027
Coal	79.763	lb	0.780
Electricity	1353.596	kWh	4.618
Crude Oil	0.010	gal	0.001
Distillate Oil	3.881	gal	0.499
Gasoline	0.139	gal	0.016
LPG	0.085	gal	0.007
MISC: Process off-gas from Oil	65.881	lb	1.879
MISC: Process off-gas from NG	126.201	lb	3.623
MISC: Recovered Energy		x	-0.309
TOTAL			**32.655**
Feedstock Inputs	Value	Unit	
Crude Oil	78.328	gal	10.157
Natural Gas	17123.502	cu ft	16.832
TOTAL			**26.989**
Non-combustion Emissions	Value	Unit	
VOC	331.150	g	
CO	4041.677	g	
NOx	257.330	g	
PM10	102.216	g	
PM2.5	6.753	g	
SOx	11026.149	g	
CH4	7700.466	g	
N2O	0.065	g	
CO2	156840.320	g	

Notes:

Energy content calculated using GREET heating value assumptions. Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel input. Also excluded was 0.138 mmBtu of biomass energy. The model was constructed as follows: 0.713(N.American Flexible Polyol dataset)+0.285(N.Am. TDI)+[European Full Rigid PUR Foam Production –0.713(Eur Polyol) – 0.285(Eur TDI)]

Flexible Polyurethane Foam Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil		2.684	gal	0.377
Diesel		1.837	gal	0.236
Crude Oil		0.000	gal	0.000
Natural Gas		323.403	cu ft	0.318
Electricity		18.384	kWh	0.063
TOTAL				**0.993**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil	25.310	gal	0.106
Diesel	2.051	gal	0.008
Natural gas	18662.542	cu ft	0.545
Coal	79.763	lb	0.023
Electricity	1371.980	kWh	0.139
Crude Oil	0.010	gal	0.000
Distillate Oil	3.881	gal	0.015
Gasoline	0.139	gal	0.000
LPG	0.085	gal	0.000
MISC: Process off-gas from Oil	65.881	lb	0.056
MISC: Process off-gas from NG	126.201	lb	0.108
MISC: Recovered Energy		x	-0.009
TOTAL			**33.648**

Notes:

Upstream energy included in the European portion of transportation data was removed by applying the delivered fuel energy to total energy ratio for each fuel. This ratio was unique to each data set.

Comparison of Flexible PUR Foam Data

	Updated Values	Previously in GREET	Industry Source PlasticsEurope
Energy Use (mmBTU/ton)			
Total Energy	68.704	–	87.824
Fossil fuels	67.081	–	77.681
Coal	8.394	–	9.447
Natural gas	42.352	–	38.456
Petroleum	16.335	–	29.777
Total Emissions(g/ton)			
VOC	627.918	–	5.207
CO	5216.203	–	4897.114
NOx	3919.177	–	8358.749
PM10	1907.986	–	5774.393
PM2.5	617.765	–	
SOx	14442.348	–	11612.792
CH4	13066.711	–	29588.073
N2O	38.040	–	17.595
CO2	3,009,784	–	3,523,618
CO2 (VOC, CO, CO2)	3,019,938	–	3,531,433
GHGs	3,357,942	–	4,227,904

Notes:

Energy data from PlasticsEurope is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.
Recovered energy (0.302 mmBtu/ton) was incorporated into the natural gas, fossil fuels, and total energy calculations.

Rigid Polyurethane Foam Production

Reference Unit: 1 ton of Rigid Polyurethane Foam
Principal Data Source(s): Plastics Division of the ACC and PlasticsEurope
Geographic Location: North America and Europe
Timeframe: 1990-1993, 1996, 2003-2004, 2007
Description:

Inventory of cradle to semi-finished product for rigid polyurethane (PUR) foam. Data for precursors is North American. Data for foam production is calculated from European data.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	15.840	gal	2.223
Diesel	1.820	gal	0.234
Natural gas	14851.254	cu ft	14.599
Coal	112.400	lb	1.099
Electricity	1206.505	kWh	4.117
Crude Oil	10.582	gal	1.372
Distillate Oil	2.750	gal	0.353
Gasoline	3.164	gal	0.367
LPG	0.083	gal	0.007
MISC: Process off-gas from Oil	49.200	lb	1.560
MISC: Process off-gas from NG	92.400	lb	2.594
MISC: Recovered Energy		x	-0.957
TOTAL			**28.525**
Feedstock Inputs	Value	Unit	
Crude Oil	94.054	gal	12.196
Natural Gas	15726.101	cu ft	15.459
TOTAL			**27.655**
Non-combustion Emissions	Value	Unit	
VOC	294.866	g	
CO	4566.516	g	
NOx	492.382	g	
PM10	91.332	g	
PM2.5	9.072	g	
SOx	9885.861	g	
CH4	6446.790	g	
N2O	0.000	g	
CO2	201689.711	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 3.5% of the the total fuel input.
The model was constructed as follows: 0.5(N.American Rigid Polyol dataset)+0.5(N.Am. MDI)+[European Full Rigid PUR Foam Production –0.386(Eur Polyol) – 0.616(Eur MDI)]

Rigid Polyurethane Foam Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil		1.767	gal	0.248
Diesel		2.059	gal	0.264
Crude Oil		0.049	gal	0.006
Natural Gas		287.129	cu ft	0.282
Electricity		22.776	kWh	0.078
TOTAL				**0.879**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	17.607	gal	2.471
Diesel	49.200	gal	1.560
Natural gas	15138.383	cu ft	14.881
Coal	112.400	lb	1.099
Electricity	1229.281	kWh	4.194
Crude Oil	10.631	gal	1.379
Distillate Oil	2.750	gal	0.353
Gasoline	3.164	gal	0.367
LPG	0.083	gal	0.007
MISC: Process off-gas from Oil	49.200	lb	1.560
MISC: Process off-gas from NG	92.400	lb	2.594
MISC: Recovered Energy		x	-0.957
TOTAL			**29.403**

Notes:

Upstream energy included in the European portion of transportation data was removed by applying the delivered fuel energy to total energy ratio for each fuel. This ratio was unique to each data set.

Comparison of Rigid PUR Foam Data

	Updated Values	Previously in GREET	Industry Source PlasticsEurope
Energy Use (mmBTU/ton)			
Total Energy	64.253	–	87.260
Fossil fuels	62.804	–	78.748
Coal	7.899	–	9.553
Natural gas	36.054	–	37.473
Petroleum	18.851	–	31.720
Total Emissions(g/ton)			
VOC	570.197	–	10.160
CO	5578.136	–	4491.955
NOx	3900.995	–	7437.353
PM10	1839.692	–	3878.925
PM2.5	611.325	–	
SOx	13544.816	–	10229.836
CH4	11104.096	–	29397.384
N2O	35.504	–	9.530
CO2	2,681,401	–	3,073,533
CO2 (VOC, CO, CO2)	2,691,944	–	3,080,719
GHGs	2,980,126	–	3,778,080

Notes:

Energy data from PlasticsEurope is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.
Recovered energy (2.288 mmBtu/ton) was incorporated into the natural gas, fossil fuels, and total energy calculations.

Polyvinyl Chloride Production

Reference Unit:	1 ton of PVC Resin
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	1989-1992, 1997-2000, 2003-2004
Description:	

Cradle to resin inventory for polyvinyl chloride (PVC) resin production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	0.820	gal	0.115
Diesel	0.009	gal	0.001
Natural gas	15248.000	cu ft	14.989
Coal	44.600	lb	0.436
Electricity	762.000	kWh	2.600
Crude Oil		gal	
Distillate Oil	1.500	gal	0.193
Gasoline	0.104	gal	0.012
LPG	0.026	gal	0.002
MISC: Process off-gas from Oil	23.600	lb	0.726
MISC: Process off-gas from NG	107.800	lb	3.304
MISC: Recovered Energy		x	-0.011
TOTAL			**22.378**
Feedstock Inputs	Value	Unit	
Crude Oil	24.682	gal	3.201
Natural Gas	16247.423	cu ft	15.971
TOTAL			**19.172**
Non-combustion Emissions	Value	Unit	
VOC	308.443	g	
CO	1188.412	g	
NOx	59.874	g	
PM10	53.524	g	
PM2.5	0.998	g	
SOx	9797.595	g	
CH4	5923.916	g	
N2O	0.000	g	
CO2	83098.122	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel. Recovered energy comprises less than 1% of total fuel inputs.

Polyvinyl Chloride Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	37.4	74.8	gal	0.051
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	264	528	gal	0.085
Barge (Diesel)	15.62	31.24	gal	0.002
Barge (Resid. Oil)		0	gal	0.006
Ocean Freighter (Diesel)	292	584	gal	0.007
Ocean Freighter (Resid. Oil)		0	gal	0.070
NG Pipeline (NG)	440	880	cu ft	0.299
Petro Pipeline (Electricity)	246	492	kWh	0.018
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL				**0.538**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	1.362	gal	0.191
Diesel	1.137	gal	0.146
Natural gas	15552.000	cu ft	15.288
Coal	44.600	lb	0.436
Electricity	767.360	kWh	2.618
Crude Oil		gal	
Distillate Oil	1.500	gal	0.193
Gasoline	0.104	gal	0.012
LPG	0.026	gal	0.002
MISC: Process off-gas from Oil	23.600	lb	0.726
MISC: Process off-gas from NG	107.800	lb	3.304
MISC: Recovered Energy		x	-0.011
TOTAL			**22.916**

Notes:

Comparison of PVC Data

	Updated Values	Previously in GREET	Industry Source Plastics Div, ACC
Energy Use (mmBTU/ton)			
Total Energy	46.769	–	51.838
Fossil fuels	45.858	–	
Coal	4.697	–	
Natural gas	36.663	–	
Petroleum	4.498	–	
Total Emissions(g/ton)			
VOC	477.579	–	738.549
CO	1729.824	–	3020.333
NOx	1883.981	–	3626.604
PM10	984.973	–	253.532
PM2.5	291.827	–	1.213
SOx	11382.554	–	12345.887
CH4	9717.414	–	13558.429
N2O	26.551	–	42.990
CO2	1,828,459	–	2,013,151
CO2 (VOC, CO, CO2)	1,832,665	–	2,020,286
GHGs	2,083,513	–	2,354,537

Notes:

Energy data from Plastics Division of the ACC is in terms of HHV.
Distillate fuel was modeled as diesel in GREET 2.7.

Flexible PUR Foam Production

Reference Unit: 1 ton of flexible PUR foam
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 1996
Description:

Cradle to precursor inventory for flexible PUR foam production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	22239.073	cu ft	21.861
Coal		lb	
Electricity	1792.413	kWh	6.116
Crude Oil	89.827	gal	11.648
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**39.625**
Feedstock Inputs	Value	Unit	
Crude Oil	110.743	gal	14.360
Natural Gas	12359.352	cu ft	12.149
TOTAL			**26.509**
Non-combustion Emissions	Value	Unit	
VOC	5.134	g	
CO	1181.716	g	
NOx	573.472	g	
PM10	4274.781	g	
PM2.5		g	
SOx	331.669	g	
CH4	1702.064	g	
N2O	0.058	g	
CO2	507331.807	g	

Notes:

Energy content calculated using GREET heating value assumptions.

Flexible PUR Foam Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.591	gal	0.206
Natural Gas		82.562	cu ft	0.081
Electricity		103.919	kWh	0.355
TOTAL				**0.642**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	22321.635	cu ft	21.942
Coal		lb	
Electricity	1896.332	kWh	6.471
Crude Oil	91.418	gal	11.854
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**40.267**

Notes:

MDI Production (European)

Reference Unit: 1 ton of MDI
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 1995
Description:

Cradle to precursor inventory for MDI production (in Europe).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	22357.957	cu ft	21.978
Coal		lb	
Electricity	1157.485	kWh	3.949
Crude Oil	66.53	gal	8.627
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**34.554**
Feedstock Inputs	Value	Unit	
Crude Oil	100.474	gal	13.028
Natural Gas	14031.319	cu ft	13.793
TOTAL			**26.821**
Non-combustion Emissions	Value	Unit	
VOC	13.027	g	
CO	778.908	g	
NOx	662.888	g	
PM10	170.552	g	
PM2.5		g	
SOx	272.576	g	
CH4	2299.202	g	
N2O	0.007	g	
CO2	360462.196	g	

Notes:

Energy content calculated using GREET heating value assumptions.

MDI Production (European) (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.264	gal	0.164
Natural Gas		96.206	cu ft	0.095
Electricity		92.495	kWh	0.316
TOTAL				**0.574**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	22454.164	cu ft	22.072
Coal		lb	
Electricity	1249.979	kWh	4.265
Crude Oil	67.795	gal	8.791
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**35.128**

Notes:

MDI Production

Reference Unit: 1 ton of MDI
Principal Data Source(s): Plastics Division of the ACC
Geographic Location: North America
Timeframe: 2003-2004, 2007
Description:

Cradle to precursor inventory of MDI production.

MATERIAL PRODUCTION DATA (Excluding Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil	5.68	gal	0.797
Diesel	0.00052	gal	0.000
Natural gas	12522	cu ft	12.309
Coal	30.8	lb	0.301
Electricity	586	kWh	1.999
Crude Oil		gal	
Distillate Oil	1.48	gal	0.190
Gasoline	0.128	gal	0.015
LPG	0.096	gal	0.008
MISC: Process off-gas from Oil	20.6	lb	0.906
MISC: Process off-gas from NG	46.4	lb	1.252
MISC: Recovered Energy		x	-1.912
TOTAL			**17.778**
Feedstock Inputs	Value	Unit	
Crude Oil	96.239	gal	12.479
Natural Gas	15298.969	cu ft	15.039
TOTAL			**27.518**
Non-combustion Emissions	Value	Unit	
VOC	272.155	g	
CO	5942.06	g	
NOx	498.952	g	
PM10	52.617	g	
PM2.5	9.072	g	
SOx	9344.003	g	
CH4	6078.138	g	
N2O	0	g	
CO2	332,937	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel.

MDI Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	13.24	0.138	gal	0.018
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	66.6	0.166	gal	0.021
Barge (Diesel)	118.8	0.096	gal	0.012
Barge (Resid. Oil)		0.32	gal	0.045
Ocean Freighter (Diesel)	1052	0.2	gal	0.026
Ocean Freighter (Resid. Oil)		1.8	gal	0.253
NG Pipeline (NG)	384	266	cu ft	0.261
Petro Pipeline (Electricity)	304	6.62	kWh	0.023
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL	**1938.64**			**0.659**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	7.8	gal	1.095
Diesel	0.601	gal	0.077
Natural gas	12788	cu ft	12.571
Coal	30.8	lb	0.301
Electricity	592.62	kWh	2.022
Crude Oil		gal	
Distillate Oil	1.48	gal	0.19
Gasoline	0.128	gal	0.015
LPG	0.096	gal	0.008
MISC: Process off-gas from Oil	20.6	lb	0.906
MISC: Process off-gas from NG	46.4	lb	1.252
MISC: Recovered Energy	x	x	-1.912
TOTAL			**18.437**

Notes:

Polyol for Flexible PUR Foam Production

Reference Unit:	1 ton of polyol for flexible PUR foam
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	1990-1993, 2003,2005

Description:

Cradle to precursor inventory of polyol for flexible polyurethane (PUR) foam production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	29.4	gal	4.126
Diesel	0.3	gal	0.039
Natural gas	19362	cu ft	19.033
Coal	97.8	lb	0.956
Electricity	1160	kWh	3.958
Crude Oil		gal	
Distillate Oil	4.82	gal	0.619
Gasoline	0.162	gal	0.019
LPG	0.084	gal	0.007
MISC: Process off-gas from Oil	92.4	lb	2.636
MISC: Process off-gas from NG	177	lb	5.082
MISC: Recovered Energy	x	x	-0.163
TOTAL			**36.475**
Feedstock Inputs	Value	Unit	
Crude Oil	73.878	gal	9.580
Natural Gas	21237.113	cu ft	20.876
TOTAL			**30.456**
Non-combustion Emissions	Value	Unit	
VOC	417.305	g	
CO	3637.811	g	
NOx	154.221	g	
PM10	136.078	g	
PM2.5	9.072	g	
SOx	13698.49	g	
CH4	9434.721	g	
N2O	0.091	g	
CO2	139706.45	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel.
Also excluded was 0.194 mmBtu of biomass energy.

Polyol for Flexible PUR Foam Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	170	1.78	gal	0.229
Single Unit (Diesel)	1.58	0.036	gal	0.005
Rail (Diesel)	81.6	0.2	gal	0.026
Barge (Diesel)	48.8	0.04	gal	0.005
Barge (Resid. Oil)		0.13	gal	0.018
Ocean Freighter (Diesel)	1114	0.22	gal	0.028
Ocean Freighter (Resid. Oil)		1.9	gal	0.267
NG Pipeline (NG)	590	408	cu ft	0.401
Petro Pipeline (Electricity)	622	13.56	kWh	0.046
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL	**2627.98**			**1.025**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	29.685	gal	4.411
Diesel	0.592	gal	0.331
Natural gas	19770	cu ft	19.434
Coal	97.8	lb	0.956
Electricity	1173.56	kWh	4.004
Crude Oil		gal	
Distillate Oil	4.82	gal	0.619
Gasoline	0.162	gal	0.019
LPG	0.084	gal	0.007
MISC: Process off-gas from Oil	92.4	lb	2.636
MISC: Process off-gas from NG	177	lb	5.082
MISC: Recovered Energy	x	x	-0.163
TOTAL			**37.499**

Notes:

Polyol for Rigid PUR Foam Production

Reference Unit:	1 ton of polyol for rigid PUR foam
Principal Data Source(s):	Plastics Division of the ACC
Geographic Location:	North America
Timeframe:	1990-1993, 2003
Description:	

Cradle to precursor inventory of polyol for rigid polyurethane (PUR) foam production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	26	gal	3.649
Diesel	3.64	gal	0.468
Natural gas	16888	cu ft	16.601
Coal	194	lb	1.896
Electricity	1064	kWh	3.630
Crude Oil		gal	
Distillate Oil	4.02	gal	0.516
Gasoline	6.2	gal	0.720
LPG	0.07	gal	0.006
MISC: Process off-gas from Oil	77.8	lb	2.214
MISC: Process off-gas from NG	138.4	lb	3.936
MISC: Recovered Energy		x	-0.003
TOTAL			**33.636**
Feedstock Inputs	Value	Unit	
Crude Oil	61.423	gal	7.965
Natural Gas	16000.000	cu ft	15.728
TOTAL			**23.693**
Non-combustion Emissions	Value	Unit	
VOC	317.515	g	
CO	3120.716	g	
NOx	462.664	g	
PM10	99.79	g	
PM2.5	9.072	g	
SOx	10341.906	g	
CH4	6558.946	g	
N2O	0	g	
CO2	57,334	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel.

Polyol for Rigid PUR Foam Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	300	3.16	gal	0.406
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	73	0.18	gal	0.023
Barge (Diesel)	42.6	0.034	gal	0.004
Barge (Resid. Oil)		0.114	gal	0.016
Ocean Freighter (Diesel)	756	0.144	gal	0.018
Ocean Freighter (Resid. Oil)		1.3	gal	0.182
NG Pipeline (NG)	448	308	cu ft	0.303
Petro Pipeline (Electricity)	534	11.64	kWh	0.040
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL	**2153.6**			**0.993**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	27.414	gal	3.848
Diesel	7.158	gal	0.919
Natural gas	17196	cu ft	16.904
Coal	194	lb	1.896
Electricity	1075.64	kWh	3.670
Crude Oil		gal	
Distillate Oil	4.02	gal	0.516
Gasoline	6.2	gal	0.720
LPG	0.07	gal	0.006
MISC: Process off-gas from Oil	77.8	lb	2.214
MISC: Process off-gas from NG	138.4	lb	3.936
MISC: Recovered Energy	x	x	-0.003
TOTAL			**34.629**

Notes:

Polyol Production (European)

Reference Unit: 1 ton of polyol
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 2008
Description:

Cradle to precursor inventory for polyol production (in Europe).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	17618.776	cu ft	17.319
Coal		lb	
Electricity	1408.002	kWh	4.804
Crude Oil	93.373	gal	12.108
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**34.231**
Feedstock Inputs	Value	Unit	
Crude Oil	118.598	gal	15.379
Natural Gas	12784.881	cu ft	12.568
TOTAL			**27.946**
Non-combustion Emissions	Value	Unit	
VOC	5.278	g	
CO	397.006	g	
NOx	324.585	g	
PM10	5566.470	g	
PM2.5		g	
SOx	375.152	g	
CH4	1885.412	g	
N2O	0.082	g	
CO2	331245.541	g	

Notes:

Energy content calculated using GREET heating value assumptions.

Polyol Production (European) (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.647	gal	0.214
Natural Gas		54.908	cu ft	0.054
Electricity		106.311	kWh	0.363
TOTAL				**0.630**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	17673.684	cu ft	17.373
Coal		lb	
Electricity	1514.313	kWh	5.167
Crude Oil	95.02	gal	12.321
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**34.862**

Notes:

Rigid PUR Foam Production

Reference Unit:	1 ton of rigid PUR foam
Principal Data Source(s):	PlasticsEurope
Geographic Location:	Europe
Timeframe:	1996
Description:	

Cradle to precursor inventory for rigid PUR foam production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	20719.603	cu ft	20.367
Coal		lb	
Electricity	1638.004	kWh	5.589
Crude Oil	87.607	gal	11.36
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**37.316**
Feedstock Inputs	Value	Unit	
Crude Oil	122.893	gal	15.936
Natural Gas	13654.873	cu ft	13.423
TOTAL			**29.35832894**
Non-combustion Emissions	Value	Unit	
VOC	10.093	g	
CO	668.180	g	
NOx	545.203	g	
PM10	2268.846	g	
PM2.5		g	
SOx	355.623	g	
CH4	2272.326	g	
N2O	0.036	g	
CO2	356459.765	g	

Notes:

Energy content calculated using GREET heating value assumptions.

Rigid PUR Foam Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.463	gal	0.190
Natural Gas		80.587	cu ft	0.079
Electricity		111.659	kWh	0.381
TOTAL				**0.650**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	20800.19	cu ft	20.447
Coal		lb	
Electricity	1749.663	kWh	5.970
Crude Oil	89.07	gal	11.550
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**37.966**

Notes:

TDI Production (European)

Reference Unit: 1 ton of TDI
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 1995
Description:

Cradle to precursor inventory for TDI production (in Europe).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	33969.096	cu ft	33.392
Coal		lb	
Electricity	1443.269	kWh	4.925
Crude Oil	81.552	gal	10.575
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**48.891**
Feedstock Inputs	Value	Unit	
Crude Oil	91.870	gal	11.913
Natural Gas	11356.930	cu ft	11.164
TOTAL			**23.077**
Non-combustion Emissions	Value	Unit	
VOC	4.808	g	
CO	3152.981	g	
NOx	1200.157	g	
PM10	1073.216	g	
PM2.5		g	
SOx	225.218	g	
CH4	1250.505	g	
N2O	0.000	g	
CO2	789075.565	g	

Notes:

Energy content calculated using GREET heating value assumptions.

TDI Production (European) (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Combination truck (Diesel)			gal	
Single Unit (Diesel)			gal	
Rail (Diesel)			gal	
Barge (Diesel)			gal	
Barge (Resid. Oil)			gal	
Ocean Freighter (Diesel)			gal	
Ocean Freighter (Resid. Oil)			gal	
NG Pipeline (NG)			cu ft	
Petro Pipeline (Electricity)			kWh	
Residual Oil			gal	
Diesel			gal	
Crude Oil		1.462	gal	0.190
Natural Gas		152.294	cu ft	0.150
Electricity		74.483	kWh	0.254
TOTAL				**0.593**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units Value	Physical Units Unit	Energy Content (MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas	34121.39	cu ft	33.541
Coal		lb	
Electricity	1517.752	kWh	5.179
Crude Oil	83.014	gal	10.764
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**49.484**

Notes:

TDI Production

Reference Unit: 1 ton of TDI
Principal Data Source(s): Plastics Division of the ACC
Geographic Location: North America
Timeframe: Early 1990's, 2003
Description:

Cradle to precursor inventory of TDI production.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil	5.84	gal	0.820
Diesel	0	gal	0.000
Natural gas	15924	cu ft	15.653
Coal	35.2	lb	0.344
Electricity	524	kWh	1.788
Crude Oil		gal	
Distillate Oil	1.56	gal	0.200
Gasoline	0.082	gal	0.010
LPG	0.088	gal	0.007
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	-0.676
TOTAL			**18.822**
Feedstock Inputs	Value	Unit	
Crude Oil	90.012	gal	11.672
Natural Gas	6927.835	cu ft	6.810
TOTAL			**18.482**
Non-combustion Emissions	Value	Unit	
VOC	117.934	g	
CO	5080.235	g	
NOx	517.095	g	
PM10	18.144	g	
PM2.5	0.998	g	
SOx	4417.99	g	
CH4	3411.015	g	
N2O	0.000	g	
CO2	38,465	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Recovered energy was not included in the totals as the credit could not be attributed to a specific fuel.

TDI Production (cont'd)

TRANSPORT DATA

Transport Method (Fuel Used)	Ton-miles	Physical Units		Energy Content
		Value	Unit	(MMBtu)
Combination truck (Diesel)	12.66	0.132	gal	0.017
Single Unit (Diesel)	0	0	gal	0.000
Rail (Diesel)	47.2	0.118	gal	0.015
Barge (Diesel)	51.8	0.042	gal	0.005
Barge (Resid. Oil)		0.138	gal	0.019
Ocean Freighter (Diesel)	2452	0.46	gal	0.059
Ocean Freighter (Resid. Oil)		4.2	gal	0.589
NG Pipeline (NG)	165.4	114	cu ft	0.112
Petro Pipeline (Electricity)	294	6.4	kWh	0.022
Residual Oil			gal	
Diesel			gal	
Crude Oil			gal	
Natural Gas			cu ft	
Electricity			kWh	
TOTAL	**3023.06**			**0.839**

MATERIAL PRODUCTION DATA (Including Transport)

Fuel Inputs	Physical Units		Energy Content
	Value	Unit	(MMBtu)
Resid. oil	10.178	gal	1.429
Diesel	0.752	gal	0.097
Natural gas	16038	cu ft	15.765
Coal	35.2	lb	0.344
Electricity	530.4	kWh	1.810
Crude Oil		gal	
Distillate Oil	1.56	gal	0.200
Gasoline	0.082	gal	0.010
LPG	0.088	gal	0.007
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy	x	x	-0.676
TOTAL			**19.662**

Notes:

Blow Molding HDPE

Reference Unit: 1 ton of Blow Molded HDPE Product
Principal Data Source(s): 2005 report from PlasticsEurope by Ian Boustead
Geographic Location: Europe
Timeframe:
Description:

Blow molding HDPE (as bottles).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel	0.013	gal	0.002
Natural gas		cu ft	
Coal		lb	
Electricity	1550.895	kWh	5.292
Crude Oil		gal	
Distillate Oil	0.007	gal	0.001
Gasoline		gal	
LPG	0.230	gal	0.019
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**5.314**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Blow Molded HDPE Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	13.596	–
Fossil fuels	11.760	–
Coal	8.575	–
Natural gas	2.834	–
Petroleum	0.351	–
Total Emissions(g/ton)		
VOC	100.454	–
CO	291.882	–
NOx	1193.038	–
PM10	1520.841	–
PM2.5	399.732	–
SOx	2618.289	–
CH4	1521.840	–
N2O	14.887	–
CO2	1,129,300	–
CO2 (VOC, CO, CO2)	1,130,071	–
GHGs	1,172,554	–

Notes:

HDPE Extrusion

Reference Unit:	1 ton of Extruded HDPE Product
Principal Data Source(s):	PlasticsEurope
Geographic Location:	Europe
Timeframe:	2007
Description:	

HDPE Extrusion (as pipe)

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	496.760	kWh	1.695
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.695**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Extruded HDPE Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	4.347	–
Fossil fuels	3.759	–
Coal	2.747	–
Natural gas	0.907	–
Petroleum	0.105	–
Total Emissions(g/ton)		
VOC	32.055	–
CO	92.474	–
NOx	380.607	–
PM10	486.988	–
PM2.5	127.943	–
SOx	837.100	–
CH4	486.745	–
N2O	4.760	–
CO2	360,903	–
CO2 (VOC, CO, CO2)	361,148	–
GHGs	374,735	–

Notes:

HDPE Injection Molding

Reference Unit:	1 ton of Injection Molded HDPE Product
Principal Data Source(s):	PlasticsEurope
Geographic Location:	Europe
Timeframe:	2007
Description:	

Injection molding HDPE resin.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	1812.734	kWh	6.185
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**6.185**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Injection Molded HDPE Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	15.862	–
Fossil fuels	13.715	–
Coal	10.022	–
Natural gas	3.310	–
Petroleum	0.383	–
Total Emissions(g/ton)		
VOC	116.969	–
CO	337.434	–
NOx	1388.821	–
PM10	1777.002	–
PM2.5	466.858	–
SOx	3054.551	–
CH4	1776.118	–
N2O	17.368	–
CO2	1,316,922	–
CO2 (VOC, CO, CO2)	1,317,817	–
GHGs	1,367,395	–

Notes:

Extrusion of PP

Reference Unit:	1 ton of Extruded PP Product
Principal Data Source(s):	PlasticsEurope
Geographic Location:	Europe
Timeframe:	2007
Description:	

Extrusion of PP (as pipe).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	635.282	kWh	2.168
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**2.168**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Extruded PP Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	5.560	–
Fossil fuels	4.808	–
Coal	3.513	–
Natural gas	1.160	–
Petroleum	0.134	–
Total Emissions(g/ton)		
VOC	41.001	–
CO	118.279	–
NOx	486.817	–
PM10	622.885	–
PM2.5	163.646	–
SOx	1070.698	–
CH4	622.574	–
N2O	6.088	–
CO2	461,615	–
CO2 (VOC, CO, CO2)	461,928	–
GHGs	479,307	–

Notes:

PP Injection Molding

Reference Unit: 1 ton of Injection Molded PP Product
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 2007
Description:

Injection molding of PP resin.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	725.043	kWh	2.474
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**2.474**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Injection Molded PP Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	6.345	–
Fossil fuels	5.486	–
Coal	4.009	–
Natural gas	1.324	–
Petroleum	0.153	–
Total Emissions(g/ton)		
VOC	46.788	–
CO	134.974	–
NOx	555.529	–
PM10	710.801	–
PM2.5	186.743	–
SOx	1221.820	–
CH4	710.447	–
N2O	6.947	–
CO2	526,769	–
CO2 (VOC, CO, CO2)	527,127	–
GHGs	546,958	–

Notes:

PVC Calendaring

Reference Unit: 1 ton of Calendared PVC Product
Principal Data Source(s): PlasticsEurope
Geographic Location: Germany
Timeframe: 2007
Description:

Calendaring of PVC resin (as film).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	527.075	kWh	1.798
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.798**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO	2.118	g	
NOx	0.015	g	
PM10	37.909	g	
PM2.5		g	
SOx	0.015	g	
CH4		g	
N2O		g	
CO2	22.727	g	

Notes:

Energy content calculated using GREET heating value assumptions.
Particulates (unspecified size) were included in PM10.

Comparison of Calendared PVC Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	4.611	–
Fossil fuels	3.987	–
Coal	2.914	–
Natural gas	0.962	–
Petroleum	0.111	–
Total Emissions(g/ton)		
VOC	34.003	–
CO	100.211	–
NOx	403.750	–
PM10	554.489	–
PM2.5	135.717	–
SOx	887.983	–
CH4	516.323	–
N2O	5.049	–
CO2	382856.347	–
CO2 (VOC, CO, CO2)	383,120	–
GHGs	397,532	–

Notes:

PVC Extrusion

Reference Unit: 1 ton of Extruded PVC Product
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 2007
Description:

Extrusion of PVC resin (as pipe).

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	478.742	kWh	1.633
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**1.633**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Extruded PVC Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	4.188	–
Fossil fuels	3.621	–
Coal	2.646	–
Natural gas	0.874	–
Petroleum	0.101	–
Total Emissions(g/ton)		
VOC	30.883	–
CO	89.091	–
NOx	366.685	–
PM10	469.175	–
PM2.5	123.263	–
SOx	806.480	–
CH4	468.941	–
N2O	4.586	–
CO2	347,701.50	–
CO2 (VOC, CO, CO2)	347,937.76	–
GHGs	361,027.77	–

Notes:

PVC Injection Molding

Reference Unit: 1 ton of Injection Molded PVC Product
Principal Data Source(s): PlasticsEurope
Geographic Location: Europe
Timeframe: 2007
Description:

Injection molding of PVC resin.

MATERIAL PRODUCTION DATA (Excluding Transport)

	Physical Units		Energy Content
Fuel Inputs	Value	Unit	(MMBtu)
Resid. oil		gal	
Diesel		gal	
Natural gas		cu ft	
Coal		lb	
Electricity	1114.730	kWh	3.803
Crude Oil		gal	
Distillate Oil		gal	
Gasoline		gal	
LPG		gal	
MISC: Process off-gas from Oil		lb	
MISC: Process off-gas from NG		lb	
MISC: Recovered Energy		x	
TOTAL			**3.803**
Feedstock Inputs	Value	Unit	
Crude Oil		gal	
Natural Gas		cu ft	
TOTAL			
Non-combustion Emissions	Value	Unit	
VOC		g	
CO		g	
NOx		g	
PM10		g	
PM2.5		g	
SOx		g	
CH4		g	
N2O		g	
CO2		g	

Notes:

Energy content calculated using GREET heating value assumptions.

Comparison of Injection Molded PVC Data

	Updated Values	Previously in GREET
Energy Use (mmBTU/ton)		
Total Energy	9.753	–
Fossil fuels	8.433	–
Coal	6.163	–
Natural gas	2.035	–
Petroleum	0.235	–
Total Emissions(g/ton)		
VOC	71.922	–
CO	207.480	–
NOx	853.951	–
PM10	1092.634	–
PM2.5	287.059	–
SOx	1878.166	–
CH4	1092.090	–
N2O	10.679	–
CO2	809,742	–
CO2 (VOC, CO, CO2)	810,292	–
GHGs	840,777	–

Notes: