CORRIM: Phase II Final Report

Module H

Resins: A Life-Cycle Inventory of Manufacturing Resins Used in the Wood Composites Industry

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Executive Summary

The objective of this study was to develop a life-cycle inventory (LCI) for the production of resins in the U.S. used to manufacture wood composites. The resins documented included urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), and phenol-resorcinol-formaldehyde (PRF). The data are needed to scientifically document the favorable environmental performance of the use of resins in the manufacture of wood-based composites for such product applications as governed by the many new green building standards, purchasing guidelines, environmental declarations, energy and global warming related policies.

A LCI of a product consists of all inputs and outputs involved its production traced back to their in-ground resources. To obtain the resin production data a survey was conducted of manufacturers for the production year 2005. U.S. plants were surveyed that represented approximately 2/3rds of production for these resins for the wood composites industry. The resin industry that year produced for wood composites about 1.23 billion kg of liquid UF resin at 65% solids, 86.6 million kg of liquid MUF at 60% solids, 779 million kg of liquid PF at 47.4% solids, and 15.5 million kg of liquid PRF resin at 60% solids. These production values are for resin used in the wood products industry, additional resins are produced for other industries. In the wood composites industry UF resin is used to produce particleboard, medium density fiberboard, and hardwood plywood, MUF is used to impart increased moisture resistance to the same products produced with UF resin, PF is used to produce softwood plywood, laminated veneer lumber, oriented strand board, and hardboard, and PRF is used to produce laminated timbers and I-joists.

The quality of the surveyed data was found to be high based on the similarity of between resin plant data, expected molar ratio of formaldehyde to urea, melamine, phenol, resorcinol or some combination of these chemicals, and the mass flows considering that the chemical reactions involve condensation which produces additional water.

The LCI study was conducted based on ISO 14040 and 14044 international standards and CORRIM protocol which specify methodology, analyses and reporting components and format. To conduct the LCI an environmental software package—SimaPro—was used. Within this package the Franklin Associates Limited database was used to provide the environmental inputs for fuel, electricity and transportation impacts for the U.S., and the Ecoinvent database for European production of chemicals was modified to U.S. fuel, electricity, and transportation impacts and used for impacts of input chemicals. The LCI provides a comprehensive listing of all inputs to the process that include the use of resources, electricity, chemicals, fuels, and transportation, and a listing of outputs such as resin, emissions to air, water, and land, and waste. In addition to LCI values the embodied energy and carbon footprint were calculated for each resin.

The production of these four formaldehyde-based resins was done in two process steps. First methanol was reacted with a metal catalyst in a reactor to produce formaldehyde, and then the formaldehyde was reacted with one or more of the following: urea, melamine, phenol, and resorcinol to produce the desired resin. To model the environmental impacts of production a single black-box approach representing the two processes was selected since all burdens are assigned to the resin (no co-products are produced) and there was no benefit to assigning individual fuel, electricity, and emissions to each unit process.

Environmental impacts were assessed for those at the resin manufacturing site (referred to as on-site system boundary) and those for cradle-to-product gate system boundary which begins with resources in the ground through extraction, generation, delivery, and resin manufacture. On-site impacts were generally found to be smaller compared to the cradle-to-gate impacts. The on-site air emissions for most gases except for those chemicals generated on-site were only a small percentage of the cradle-to-gate emissions; e.g., for UF resin production, emissions to air such as CO_2, CO, VOCs, particulate, formaldehyde and methanol are 1%, 1%, 100%, 1%, 69% and 3% for the on-site compared to the cradle-to-gate values. The on-site emissions to water and land are also smaller. Likewise, the embodied energy to account for feedstock, fuel and electricity use was much smaller for the on-site boundary than for the cradle-to-gate boundary; e.g., for 1.0 kg of liquid UF resin the on-site energy use is 0.39 MJ compared to 29.4 MJ for the cradle-to-product gate energy. Overall the resin operations are resource efficient and relatively friendly to the environment.

The cradle-to-gate embodied energy to produce resins which consisted of fuels, feedstock and electricity was dependent on resin type. The primary input chemicals of methanol, urea, melamine, phenol, and resorcinol are all based on natural gas and/or crude oil as an in-ground resource feedstock. The embodied energy per 1.0 kg of liquid resin was as follows: 29.4 MJ for UF, 31.7 MJ for MUF, 40.4 MJ for PF, and 40.5 MJ for PRF. For all resin systems the dominant contributors to the embodied energy were the production of the primary input chemicals of methanol, urea, melamine, and phenol; no LCI data existed for resorcinol in the available databases. All other contributors such as caustics, acids, transportation, and on-site fuel and electricity had smaller contributions.

A sensitivity analysis was conducted by examining the contribution of each input in the cradle-to-gate analysis to the major emissions to air, water and land. Included were on-site inputs of transportation, chemicals, fuels and electricity. For all resins the dominant contributors were the input primary chemicals of methanol, urea, melamine, and phenol (no LCI data could be found in the available databases for resorcinol). The output emissions in general were dominated by the production of these chemicals; all other inputs to the resin process were minor contributors. Therefore, any changes in the amount of the primary chemicals resulted in general in a proportional change in emissions dependent on their original contribution.

The carbon footprint to manufacture a product is determined by the CO_2 equivalent (eq) of greenhouse gas (GHG) emissions to the atmosphere. The equivalent value of each is based on its reactive factor in the atmosphere compared to CO_2. For the cradle-to-gate production of resins the GHG emissions considered were CO_2, methane and nitrous oxide; contributions by other GHGs such as chlorofluorocarbons (CFCs) were insignificant. The carbon footprint was calculated for a 100% solid resin, the value of each is 2.474 kg-CO_2 eq for UF, 2.958 kg-CO_2 eq for MUF, 2.788 kg-CO_2 eq for PF, and 02.323 kg-CO_2 eq for PRF. Although these resins have significant carbon components, they are not considered as a carbon store offset for CO_2 emissions to the atmosphere since its carbon is based on fossil-fuel feedstock that was sequestered hundreds of millions of years ago and it is not a component of a continuously renewing carbon cycle.

This study provides a comprehensive database for the life-cycle inventory of formaldehyde-based resins of UF, MUF, PF, and PRF as used in the wood composites industry. The data should be used as the basis for any life-cycle assessment of its environmental performance as a component of wood composites and can be used to improve processing or to compare to alternative materials. The data can also be used to provide environmental performance measures for standards, guidelines and practices. This data will be available to the public at www.corrim.org, in a special publication of the Journal of Wood and Fiber Science, and through the U.S. LCI Database at www.nrel.gov/lci/.

To obtain full benefit from the availability of the LCI database for these formaldehyde-based resins, the following additional studies are recommended: 1) extract pertinent data to document their favorable environmental performance, and 2) substitute LCI data for resins developed in this study into earlier CORRIM LCI studies of wood composites to replace existing resin data from European and Canadian sources.

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1.0 Resins Used for Wood Composites Manufacture

1.1 Introduction

The objective of this study is to develop the life-cycle inventory (LCI) data for most of the primary resin systems used in the manufacture of wood composites. Resins included in the study are urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), and phenol-resorcinol-formaldehyde (PRF). An LCI consists of an accounting of all inputs and outputs of the manufacture of these resins. For this study a system boundary was selected from their in-ground resources (referred to as the cradle) through resin production—this is referred to as cradle-to-product gate.

LCI data is invaluable when it comes to establishing the environmental greenness of a product, for improving processes, and for comparison to competitive materials. The cradle-to-gate LCI data can be used for environmental production declarations (EPD). For resins, the life cycle issue is not the product itself, but more importantly as a component in the LCI analyses of wood composites such as particleboard, medium density fiberboard (MDF), oriented strand board (OSB) laminated veneer lumber (LVL), I-joists, and laminated timbers (glulam), all product databases developed by CORRIM in earlier studies. The resin acts as the enabler for these composites, providing strength, durability, performance, and enhanced wood resource use and efficiency. The LCI data forms the foundation for the scientific assessment in terms of a variety of environmental performance measures. Furthermore, the data can be used to establish the performance of wood composites for many green type standards, guidelines and policies. Issues where the data can be used are sustainability, global warming, climate change, carbon storage, carbon cap and trade, carbon taxes, green purchasing, and green building. Based on the CORRIM databases for structural wood products and a life-cycle assessment (LCA) of buildings constructed of various materials, researchers have documented the favorable environmental performance of wood products (Perez-Garcia et al. 2005); developing a database for resins when used to evaluate the LCI of wood composites can serve a similar basis for establishing their favorable environmental performance when used in wood composites manufacture.

The resins studied are thermosets in that they are cured by chemical reaction to form a cross-linked polymer that cannot be remelted or reprocessed although UF and some MUF resins may be reprocessed under the right conditions. The resins are usually applied as a liquid mix of resin, water, and possibly other ingredients to the wood during the production of wood composites. The amount of resin applied is dependant on the resin and wood composite type, and can range anywhere from 2-10% of the total composite weight. Catalyst, hardeners, heat, and pressure may be required to cure the resin. UF resins are used for interior use products such as particleboard, MDF, and hardwood plywood production. MUF resins are used to impart greater moisture and water resistance than the UF resins and can be used for the production of the same products. PF resins are even more moisture resistance and are used for exterior use products such as softwood plywood, OSB, and LVL, and are also used for hardboard. For the greatest moisture resistance, PRF resins are used to produce laminated timbers and I-joists. Not included in this study is the LCI of isocyanate adhesive that is used to produce OSB and can be used for particleboard and MDF to impart greater moisture and water resistance than UF resin. For additional background on these resin systems see the following textbooks: Technology of Wood Bonding by Allen Marra (1992) and Advanced Wood Adhesives Technology by Antonio Pizzi (1994).

The urea, melamine, and phenolic type resins were all developed in the early 20th century. Over the years these products have evolved into highly engineered products designed to meet specific processing, emissions standards, and end-use requirements. The production of thermoset resins fall into the Standard Industrial Classification (SIC) Code 2821, plastic materials and resins (U.S. Census Bureau 2008). The Source Classification Code (SCC) for urea-formaldehyde resin production is 30101832, for melamine type resin production is 30101842, and phenolic (PF) resin production is 30101805 (USEPA 2008).

The goal of this study is to document the life-cycle inventory (LCI) of manufacturing UF, MUF, PF and PRF resins in the U.S., although some Canadian production data may be included since the manufacturing process parameters are essentially the same for both countries. This study covers the environmental impacts from the natural resources such as natural gas in the ground through to production of the resin in their liquid form as shipped to the customer. The individual resin manufacturing facilities were generally able to produce all four resins, however due to market and production capacity not all resins are produced at a given site. The manufacturing data for each resin was collected by survey of the industry; the data also included transportation of input chemicals to their production facilities. The data for the various facilities were very similar with the main difference as a result of emissions control approaches and the nuances of custom resin formulations.

This study considers those impacts in the manufacture of resins, documenting all inputs of materials, fuel, and electricity, and all outputs of product and emissions to air, water and land. The boundary conditions are defined in terms of the on-site production facilities (referred to as gate-to-gate) and from resources in the ground to the production output of resin (referred to as cradle-to-product gate or simply cradle-to-gate). Primary data was collected by direct survey of resin manufacturers. The survey questionnaire is included in Appendix 1 of this report. Supplemental secondary data was obtained for impacts associated with the manufacture, delivery, and consumption of electricity, fuels, and transportation (Franklin Associates 2004, PRé Consultants 2007, USDOE 2007), and the input chemicals (Ecoinvent 2008) which were adjusted to U.S. energy and transportation values where possible.

The survey data represents resin production in terms of input materials, electricity, and fuel use, and emissions for the 2005 production year. The surveys represented about 60-70% of total U.S. production for each resin; the production facilities were representative of U.S. production practices. Resins with the largest annual production were UF (1,225,869,685 kg (2,702,552,308 lb) at 65% solids) and PF (779,063,416 kg (1,717,523,207 lb) at 47.4% solids), whereas smaller amounts were produced of MUF (86,588,648 kg (190,893,333 lb) at 60% solids) and PRF (15,513,018 kg (34,200,000 lb) at 60% solids). The resin production values are based on estimated production use for the wood composites stated above based on resin use data in CORRIM reports (Kline 2005, Puettmann and Wilson 2005, Wilson and Sakimoto 2005, Wilson and Dancer 2005a and 2005b, Wilson 2008a, and Wilson 2008b).

This report follows International Organization for Standardization (ISO) 14040 and 14044 protocol (ISO 2006a and ISO 2006b) and Consortium for Research on Renewable Industrial Materials (CORRIM) guidelines and format (CORRIM 2001); the report provides a useful database for conducting life-cycle assessment of the environmental performance of wood composites. Each resin is reported in a separate chapter following the same ISO format. The report has had a thorough technical and life-cycle review. The LCI data will be publicly available in the US LCI Database (www.nrel.gov), as this report posted on the CORRIM web site (www.corrim.org), and as a refereed article in a special issue of Wood and Fiber Science in 2010.

1.1.1 Functional or Production Unit

The functional unit for all data in this study is 1.0 kg of liquid resin at its stated non-volatile solids (NVS) content; e.g., the functional unit for UF resin is 1.0 kg at 65% solids. All data are given in SI units however for most values such as input chemicals and output emissions which are usually in units of kg solids/kg of resin at their stated use solids, the English units would have the same value with units of lb solids/lb of resin at its stated solids. To determine the life-cycle inventory data for a resin at 100% solids, divide the values in this report by the fractional value of its stated use solids percentage.

1.1.2 Survey Data Analysis

The survey data from the resin producers were analyzed for quality by assessing for outliers and determining their molar ratio of the major chemical components; mass balances were also done although these are chemical reactions so there can be differences. The data for each production facility were converted to a functional unit of production, in this case 1.0 kg of neat (with water) resin at their specified solids content to make the comparison. Any outliers were resolved by contacting the producers. The molar ratio of formaldehyde to urea, phenol, melamine, and resorcinol of each resin was calculated and all found to be within the expected range. The data for the plants were then weight-averaged based on the production of each plant and the total production for the surveyed group. Only the weight-averaged data are presented in this report. The data for all chemical inputs are given in kg on a dry or 100% solids basis per kg of neat resin at the stated solids percentage.

1.1.3 Manufacturing Process

The resin manufacturing processes for all four resins begin with the conversion of methanol by catalytic oxidation in a reactor vessel to produce an aqueous form of formaldehyde, see Figure 1.1. The methanol is first vaporized by warming, mixed with air, and then introduced into a reactor containing a metal catalyst of either silver or molybdenum/iron oxide in very small quantities. Upon exiting the reactor the formaldehyde is cooled and then sent to the absorber where it is absorbed into water to produce an aqueous solution. Heat is recovered during this process, these integrated plants capture excess steam and use elsewhere in the manufacturing process. The various formaldehyde resins are then produced in a batch reactor by reacting formaldehyde with either urea, melamine, phenol, resorcinol or some combination of these. The process involves heating the mix and controlling the reaction by controlling the temperature, pH, ratio of formaldehyde to urea, phenol, melamine, resorcinol or some combination of these chemicals, and the rate of charging until the desired degree of polymerization is achieved. The reaction is quenched and then cooled. If needed, water is stripped off to provide the desired percentage of resin solids. Most of the process water is recycled and used within the production process. Very little waste is generated by resin production. Some production facilities used regenerative thermal oxidizers (RTOs), regenerative catalytic oxidizers (RCOs) and/or wet scrubbers as emission controllers to reduce the type and percentage of some emissions. RTOs and RCOs require the additional use of electricity and natural gas for their operation. It is noteworthy that essentially all production facilities started with methanol, only a very small amount (<1%) of formaldehyde was purchased for these operations, as such it was not included in the analysis.

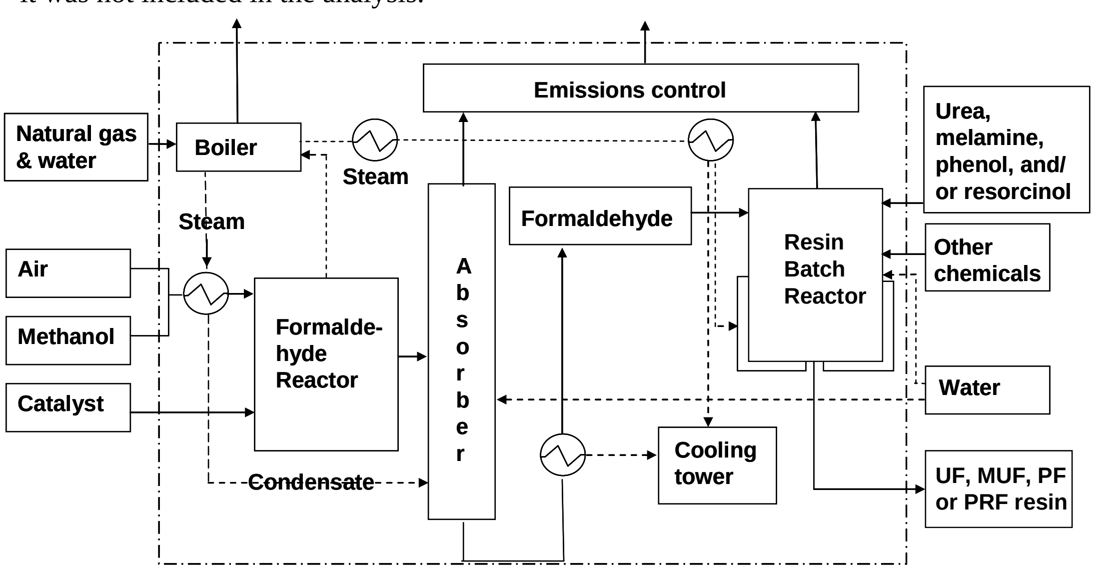

Figure 1.1. A generic process flow chart for the production of UF, MUF, PF or PRF resins.

1.1.3 System Boundary Conditions

A black-box approach was selected for modeling the life-cycle inventory of the resin manufacturing process. Whereas unit process approaches were used in earlier CORRIM studies of lumber and plywood production (Milota, et al 2005, Wilson and Sakimoto 2005), it is not needed in this case since unlike those processes that have a higher percentage of co-product that are generated at various steps throughout the process, resin production does not generate any co-products. In a black-box approach only flows into and out of the box are considered. Both an on-site and cradle-to-product gate system boundaries were considered. Figure 1.2 gives the on-site boundary that considers only site emissions and does not include those emissions for the production and delivery of chemicals, fuels, and electricity. Only those inputs and outputs directly associated with the manufacturing process are considered—those emissions that occur due to on-site combustion of fuels whether for process heat or operating equipment are considered. Figure 1.3 gives the cumulative or total emissions—referred to as cradle-to-product gate emissions—from in-ground resources of all inputs and includes the on-site emissions. All impacts are considered, including those for the manufacture and delivery of input chemicals, fuels, and electricity. The cumulative system boundary provides the cradle-to-product gate impacts from raw resources in-ground through production of the resin ready for delivery.

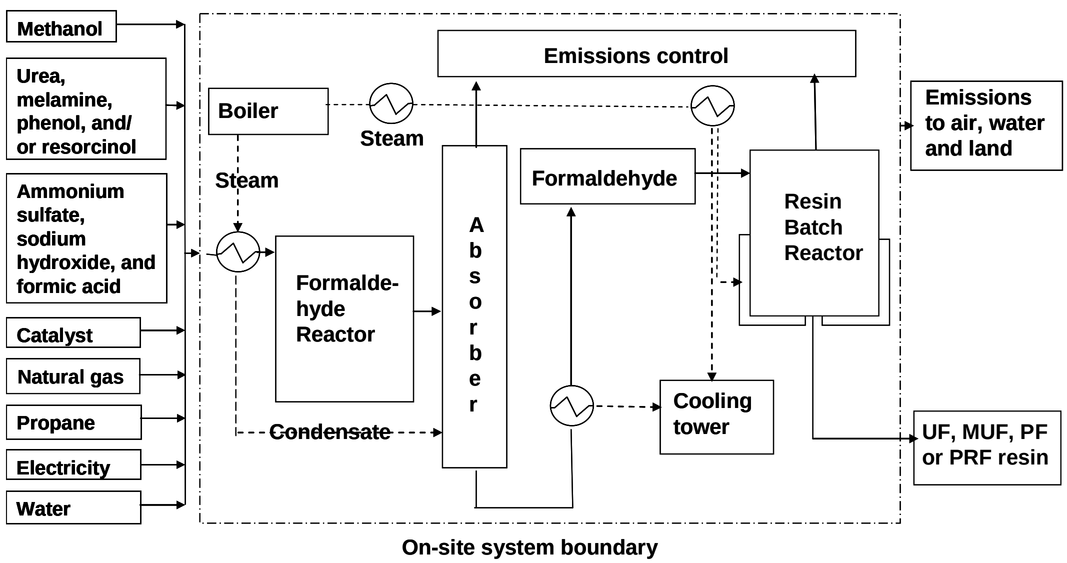

Figure 1.2. On-site system boundary for production of resin.

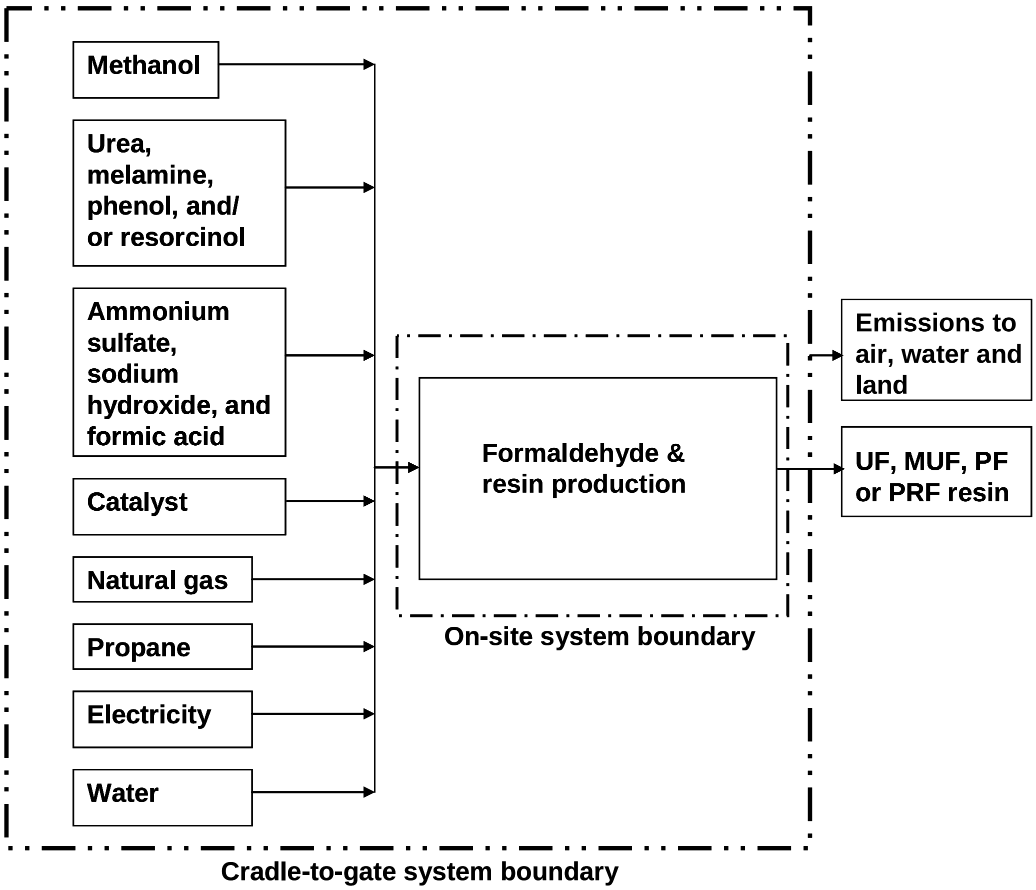

Figure 1.3. Cradle-to-product gate system boundary for producing resin.

In a cradle-to-resin gate system boundary all inputs are tracked back to their in-ground resources whether for an input chemical, fuels, or electricity. For the life-cycle inventory of many of the input chemicals and electricity they begin with natural gas or some other fossil fuel or feedstock. It is worthwhile to understand that in addition to the fuel and electricity inputs, the primary chemicals used in the production of the resins are heavily dependant on fuels for feedstock. The primary chemicals for these resins include methanol, urea, phenol, melamine, and resorcinol. Methanol is a chemical compound with a formula of CH_3OH, the simplest of alcohols, and is produced from natural gas feedstock. Urea, an organic compound with the chemical formula $(NH_2)_2CO$, is produced from ammonia which in turn was based on natural gas feedstock. Phenol, an aromatic compound with the chemical formula C_6H_5OH starts with crude oil as a feedstock but goes through several production steps of oil to benzene, benzene to cumene, and cumene to phenol to complete the process. Melamine, an organic base with a chemical formula of $C_3H_6N_6$, is also based on natural gas as a feedstock since it is produced from urea. Resorcinol, a chemical compound with the chemical formula $C_6H_4(OH)_2$, is produced from crude oil feedstock. In addition to the use of natural gas and crude oil for feedstock to produce these chemicals, additional fossil fuels are used for transportation, process heat, and generation of electricity used in their manufacture.

1.1.6 Assumptions

The data collection, analyses, and assumptions followed protocol as defined in Consortium for Research on Renewable Industrial Materials (CORRIM)—Research Guideline for Life Cycle Inventories (CORRIM 2001) and the ISO 14040 and 14044 standards for environmental management and documentation (ISO 2006a and 2006b). The environmental impact analyses were done using SimaPro

7.1 software which was developed in the Netherlands and has a Franklin Associates Ltd. (FAL) database to provide impacts for fuels and electricity for the U.S. (PRé Consultants 2007). For input chemicals not covered by the FAL database, the Ecoinvent v2.0 database (Ecoinvent 2008), a comprehensive database for Europe, was used to determine environmental impacts; however, their data were adjusted to U.S. fuels, electricity, and transportation data using FAL processes where appropriate. Additional conditions include:

- The functional unit defined for the life-cycle inventory for the production of resin from cradle-to-production gate is 1.0 kg neat (with water) at the stated non-volatile solids content of each resin. The inventory is for neat resin as sold to wood composite producers.
- All data from the survey were weight averaged based on production in comparison to their total production for the year. Where appropriate missing data from various plants were not included in weight averages.
- Mass-based allocation was used to assign environmental burdens to the resin based on the system boundary.
- A black-box approach was used to model the resin process since there were no co-products to allocate burdens to and the process is very interlinked. This approach does not impact the accuracy of assigning the environmental burdens.
- Environmental impacts were assessed for both on- and off-site resin production that included all impacts from in-ground resources through the production of input chemicals, electricity and fuels.
- To determine the energy content of fuels and feedstock, their higher heating values (HHV) were used. The HHV is defined as the amount of heat released by a fuel initially at 25^{o}C when it is combusted and the products have returned to their initial temperature. In contrast, the lower heating value (LHV) is determined when the cooling is stopped at 150^{o}C and only some of the reaction energy is recovered. The HHV provides a fuel's intrinsic property whereas the LHV is used as a practical number. The energy content values were not used to calculate inputs to the SimaPro model, rather the industry unit for fuel or feedstock of kg, L, or m^3, and for electricity MJ, were used.
- On-site emissions of CO_2 and CO were not reported in the surveys; these values were determined using Franklin Associates' database for the combustion of the various fuels based on their actual use.

1.1.7 Electricity Use in U.S. by Fuel Source

The source of fuel used to generate the electricity used in the manufacturing process is very important in determining the type and amount of environmental impact as a result of its use. The breakdown of fuel source to generate the electricity was based on the U.S. average as stated by the U.S. Energy Information Administration (EIA 2007) for 2005. The dominant fuel source was coal at 49.6%, followed by nuclear at 18.7% and natural gas at 18.7%. Table 1.1 gives a breakdown of the electricity generation by fuel source. The less contributing sources are hydroelectric at 6.7%, petroleum at 3.0% and other renewables at 2.2%, much smaller quantities are produced by other gases (0.4%) and other (0.3%). The fuel source to generate electricity is important in any life-cycle inventory since the impacts are traced back to the in-ground source of the fuel used. The efficiency to produce and deliver electricity is relatively low; generation is about 30% energy efficient. In PRé Consultants' SimaPro environmental assessment software no impacts are associated with hydro-generated electricity; whereas combustion of coal and natural gas contribute significant impact values. The generation of electricity by fuel source is used to assign environmental burdens in the SimaPro modeling of the various processes based on the FAL fuel values for the U.S.

Table 1.1. U.S. electricity data by fuel source for 2005 (EIA 2007).

Fuel source	%
Coal	49.6
Petroleum	3.0
Natural gas	18.7
From other gases	0.4
Nuclear	19.3
Hydroelectric	6.7
From renewables	2.2
Pumped storage	-0.2
Other	0.3
Total electricity industry	100

2.0 Life-Cycle Inventory of Urea-Formaldehyde Resin

2.1 Introduction

2.1.1 Survey Data

The UF resin survey data were for 16 plants in the U.S. and represented 72% of total production for the year 2005. Total annual production was 2,703,000,000 lbs (1,226,000,000 kg) of neat resin at 65% non-volatile solids content. The resin is produced for the manufacture of particleboard, medium density fiberboard (MDF) and hardwood plywood. The production data are based on resin use (Wilson 2008a, Wilson 2008b) and panel production data (CPA 2006) and estimates of resin use for hardwood plywood production. The data includes a small amount of resin for non-wood composites use.

2.1.2 Materials Flow

Those materials considered in the LCI analysis of urea-formaldehyde resin production included those listed in Table 2.1. Input materials considered were urea, methanol, formic acid, ammonium sulfate, sodium hydroxide, water and other chemicals of minor contribution totaling much less than 1% weight of resin. The silver or molybdenum/iron oxide catalyst was not included in the analysis because of its very small contribution to the analysis and the manufacturers considered this information proprietary.

Table 2.1. Listing of input chemicals used to produce urea-formaldehyde resin.

Input Material	Product
Urea (100%)[1]	Urea-formaldehyde resin (65%)[2]
Methanol (100%)	
Formic acid (10%)	
Ammonium sulfate (20%)	
Sodium hydroxide (50%)	
Water	

[1] Solids content or solution strength of chemicals into the plant.

[2] Solids content of resin out of the plant.

2.1.3 Transportation

The delivery of chemicals to the resin plants is by both truck and rail. Table 2.2 gives the one-way deliver distances. Usually the truck deliveries have no back haul of other materials. The t•km (the mass (t for tonne) times distance traveled (km)) values are used in the SimaPro software by accessing the FAL database to obtain U.S. typical impacts for truck and rail transportation. Other chemicals are used in the resin production process but their quantity and contribution to environmental impacts were so insignificant that they were not included in either the survey data or the transportation calculations.

Table 2.2. One-way delivery distance for input chemicals to UF resin plants.

	Transportation		One-way distance	Chemical weight		Truck	Rail
Chemical	**mode**	**% mode**	**km**	**kg**	**t**	**tkm**	**tkm**
Urea	truck	12	314	0.47	4.70E-04	1.77E-02	
Urea	rail	88	958	0.47	4.70E-04		3.96E-01
Methanol	truck	15	242	0.31	3.10E-04	1.13E-02	
Methanol	rail	85	1986	0.31	3.10E-04		5.23E-01
Formic acid	truck	100	347	4.75E-04	4.75E-07	1.65E-04	
Formic acid	rail	0					
Ammonium sulfate	truck	100	347	1.58E-04	1.58E-07	5.48E-05	
Ammonium sulfate	rail	0					
Sodium hydroxide	truck	100	347	4.44E-04	4.44E-07	1.54E-04	
Sodium hydroxide	rail	0		.			
Total						2.93E-02	9.20E-01

2.2 Product Yield

The inputs to produce 1.0 kg of neat urea-formaldehyde (UF) resin at 65% non-volatile solids content consist of the two primary chemicals of urea at 0.47 kg and methanol at 0.31 kg, much lesser amounts of formic acid, ammonium, and sodium hydroxide, and 0.5 kg of water. A significant portion of the processing water is recycled back into the resin. See Table 2.3 for all inputs and outputs for the manufacture of UF resin. Electricity is used for processing by fans and pumps, and for operating emissions control equipment, while the natural gas is used for boiler fuel and emission control equipment, and propane is used for fuel in forklifts.

Table 2.3. Inputs for the production of 1.0 kg of UF resin at 65% solids.

	SI Unit	Unit/kg UF 65% solids
INPUTS		
Chemicals[1]		
Urea	kg	4.73E-01
Methanol	kg	3.09E-01
Formic acid	kg	4.74E-05
Ammonium sulfate	kg	3.16E-05
Sodium hydroxide	kg	2.22E-04
Water[2]		
Water for producing UF resin	kg	3.33E-02
Water use; cooling tower	kg	4.57E-01
Water other; boiler makeup	kg	9.47E-03
Electricity and fuel use		
Electricity	kWh	1.77E-02
Electricity for emissions control	kWh	1.36E-02
Natural gas	m^3	7.34E-03
Propane	L	9.35E-06
OUTPUTS[3]		
UF liquid resin (65% solids)	kg	1.0

[1] All chemical weights given at either 100% non-volatile solids or dry except for UF resin given on a 65% solids basis.

[2] There is a significant amount of water recycling back into the resin.

[3] Emissions to air, water and land listed in separate table.

The molar ratio of formaldehyde to urea was used as a check on the quality of the data. Assuming that it takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde, the molar ratio of formaldehyde to urea for this representative resin system was determined to be 1.09 which is the expected value for a contemporary, commercial UF resin for use in the particleboard and MDF industry. The value of the molar ratio affects both the performance of the resin and the properties of the composite panel made with the resin. The value of the molar ratio also affects the quantity of formaldehyde emissions from the panel, with the lower the ratio the lower the emissions. The industry over the years has made significant strides to lower the molar ratio while maintaining favorable resin and panel properties.

2.3 Manufacturing Energy Summary

2.3.1 Sources of Energy and Electricity

Energy for the production of UF resin comes from electricity to operate fans and blowers, natural gas to generate steam (boiler) for heating reactors and input chemical, and propane gas (LPG) to operate forklift equipment. Electricity and natural gas are also used to operate regenerative thermal oxidizers (RTOs) and regenerative catalytic oxidizers (RCOs) at some plants to control air emissions. A breakdown by fuel source for the production of electricity for the U.S. in 2005 was given previously in Table 1.1.

Natural gas is the primary fuel in resin manufacturing; it is used for generating steam that is used to heat input chemicals and reactors; and is used for combusting VOCs and HAPs in RTO and RCO emission control systems. The natural gas and/or electricity use would have been greater had all resin plants used RTO and RCO emissions control devices. In addition to natural gas use, a small amount of propane fuel was used to operate fork lift trucks and handlers within the plant. Table 2.4 gives the energy use on-site for manufacturing UF resin. The natural gas provides 71% of the energy and the electricity provides 29%. The propane is an insignificant contributor to the energy use.

Table 2.4. On-site fuel and electricity use in terms of their energy equivalence for the manufacture of UF resin at 65% non-volatile solids.

Energy use[1]	Unit	Unit/kg UF resin	MJ/kg UF resin	% Use
Electricity process	MJ	6.38E-02	6.38E-02	16.2
Electricity emissions control	MJ	4.91E-02	4.91E-02	12.5
Natural gas	m^3	7.34E-03	2.81E-01	71.4
Propane	L	9.35E-06	3.56E-07	0.0
Total energy			3.94E-01	100.0

[1] Electricity at 3.6 MJ/kWh and fuels at their higher heating value (HHV) of natural gas at 54.4 MJ/kg and propane at 54.0 MJ/kg.

2.4 Plant Emissions for Producing UF Resin

Outputs for the production of 1.0 kg of UF resin at 65% solids include emissions to air, water and land, see Table 2.5. Emissions are generated due to emissions of the combustion of gases and the chemical reactions in the reactors. For combustion, only CO_2 and CO are given—both were calculated using the SimaPro software, actual natural gas use, and the FAL database for U.S. fuels—the total emissions are determined by considering natural gas and propane on-site fuel use. All other emissions were collected by survey; they include emissions to air of particulate, volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) of formaldehyde and methanol that come off of the absorber and the reactor. The dimethyl ether emissions occur for the molybdenum/iron oxide process and not at any measurable amount for the silver oxide process in the production of formaldehyde. Emissions to water include biological chemical demand (BOD), total suspended solids (TSS), solids, ammonia nitrogen (NH_3N) and formaldehyde (HCHO).

Table 2.5. On-site reported outputs for the production of 1.0 kg of UF resin at 65% non-volatile solids.

	Survey Wt. Average kg/kg UF 65% solids
Production output	
Urea-formaldehyde resin (65% solids)	1.00
Emissions to air[1]	
CO_2[2], fossil (GHG)[3]	1.56E-02
CO[2]	3.39E-05
VOC	5.14E-05
Particulate	2.31E-06
Formaldehyde (HAP)[3]	7.79E-06
Methanol (HAP)[3]	6.08E-06
Dimethyl ether	2.18E-05
Emissions to water[1]	
BOD	6.16E-04
TSS	3.66E-04
Solids	2.23E-04
Ammonia nitrogen (NH_3N)	1.21E-04
Formaldehyde (HCHO)	7.29E-05
Emissions to land[1]	
Solids	2.23E-04

[1] Emissions data reported in survey.

[2] CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant.

[3] HAP hazardous air pollutant; GHG greenhouse gas.

2.5 Cradle-to-Product Gate Process Related Resource Use and Emissions

The life-cycle inventory for the production of UF resin covers its cycle from in-ground resources through the production and delivery of input chemicals and fuels, through its manufacture of a resin as shipped to the customer. It examines the use of all resources, fuels and electricity and all emissions to air, water and land; it also includes feedstock of natural gas and crude oil used to produce some of the input chemicals. Table 2.6 gives the raw materials and energy sources, and Table 2.7 gives emissions to air, water and land for the cradle-to-gate inventory. The raw materials in the ground include coal, natural gas, limestone, crude oil, and uranium, water usage and others. Materials of quantities smaller than 1.0E-06 kg/kg of resin are not included in the listing. Because life-cycle studies involve tracing resource use back to its in-ground resources, some materials or substances can involve many steps of backtracking to their source which results in the use of a large numbers of substances, many of insignificant quantity. For this study a filter was used to remove insignificant substances from the listing. The filter varied depending on whether the emission was to air, water, or land. The exception was for substances that are highly toxic such as uranium, mercury and lead from the production of electricity where values less than the cut-off value were shown.

Some sources of energy or fuels cannot be traced back to their original resource in the ground. Such energies include "energy from hydro power," "electricity from other gases" and "electricity from renewables" which are not defined in terms of identifiable fuels are listed in a separate category defined as Energy and are given in MJ/kg of resin.

Emissions for the cradle-to-gate scenario are listed in Table 2.7. The emissions to air and water used a cut-off value of 1.0E-06 kg/kg resin, and radiation type emissions had a cut-off of 1.0E+00 Bq/kg resin. Emissions to land used a cut-off of 1.0E-06 kg/kg resin. Some emissions because of their toxicity, even though in quantities below the cut-off value, are also shown; shown are mercury and lead due to electricity generation. Raw materials and emissions for a cradle-to-product gate inventory are generally far greater than those resources and emissions that occur at the production site; the exception to this comparison are VOCs and formaldehyde; on-site contributes 100% of the VOC emissions because the databases used for fuels, chemicals, and electricity only report individual VOC emissions and not their total grouping. On-site contribution of formaldehyde emissions are 69%, this large percentage is due mainly to the fact that formaldehyde is produced on-site. The difference between on-site and cradle-to-product gate resource use can be found by comparing Tables 2.3 and 2.6, and emissions differences by comparing Tables 2.5 and 2.7.

Table 2.6. LCI output of allocated raw material use cradle-to-product gate for the production of 1.0 kg of UF resin at 65% solids.

Raw material	kg/kg UF resin
Aluminium, 24% in bauxite, 11% in crude ore, in ground	4.69E-05
Barite, 15% in crude ore, in ground	1.33E-06
Calcite, in ground	9.66E-04
Carbon dioxide, in air	2.74E-05
Clay, unspecified, in ground	2.02E-04
Coal, 26.4 MJ per kg, in ground	6.79E-02
Coal, brown, in ground	1.88E-04
Coal, hard, unspecified, in ground	1.53E-04
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.04E-06
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	5.79E-06
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.53E-06
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	7.61E-06
Fluorspar, 92%, in ground	1.62E-06
Gas, mine, off-gas, process, coal mining/m3	1.15E-06
Gas, natural, 46.8 MJ per kg, in ground	3.84E-01
Gas, natural, in ground	7.83E-05
Gravel, in ground	7.72E-03
Iron, 46% in ore, 25% in crude ore, in ground	8.35E-06
Limestone, in ground	3.92E-03
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in grou	3.00E-06
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in groun	6.05E-06
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.63E-04
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.30E-06
Oil, crude, 42 MJ per kg, in ground	1.42E-01
Oil, crude, in ground	3.06E-04
Sodium chloride, in ground	4.76E-04
Uranium, 2291 GJ per kg, in ground	2.90E-07
Uranium, in ground	8.45E-09
Water, cooling, unspecified natural origin/m3	2.76E+00
Water, lake	9.40E-05
Water, process, drinking	2.93E-01
Water, process, unspecified natural origin/kg	4.20E-01
Water, process, well, in ground	8.00E-02
Water, river	1.29E-02
Water, salt, ocean	6.62E-04
Water, salt, sole	2.23E-04
Water, unspecified natural origin/m3	6.52E-01
Water, well, in ground	3.45E-02
Wood and wood waste, 9.5 MJ per kg	2.83E-04
Wood, hard, standing	2.06E-06
Wood, soft, standing	1.15E-05
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	1.11E-05
	MJ/kg
Electricity from other gases	3.55E-03
Electricity from other renewables	2.04E-02
Energy, from hydro power	6.04E-02
Energy, gross calorific value, in biomass	2.81E-04
Energy, kinetic (in wind), converted	7.61E-05
Energy, potential (in hydropower reservoir), converted	7.86E-03
Energy, solar, converted	1.12E-06

Table 2.7. LCI output of allocated emissions cradle-to-product gate for the production of 1.0 kg of UF resin at 65% solids.

Emissions to air	kg/kg resin
Acetic acid	4.84E-06
Aldehydes, unspecified	1.93E-05
Aluminum	4.56E-06
Ammonia	1.64E-03
Benzene	5.43E-06
Butane	9.50E-06
Carbon dioxide, biogenic	4.53E-04
Carbon dioxide, fossil	1.52E+00
Carbon disulfide	1.92E-06
Carbon monoxide	2.03E-03
Carbon monoxide, fossil	1.40E-03
Dimethyl ether	2.18E-05
Dinitrogen monoxide	1.04E-05
Ethanol	1.41E-06
Formaldehyde	1.13E-05
Hydrocarbons, aliphatic, alkanes, unspecified	2.82E-06
Hydrogen chloride	1.91E-05
Hydrogen fluoride	2.38E-06
Lead	3.00E-09
Mercury	6.77E-09
Methane	2.82E-03
Methane, biogenic	2.41E-06
Methane, fossil	6.81E-04
Methanol	1.73E-04
Methyl formate	1.25E-06
Nickel	3.24E-06
Nitrogen oxides	3.40E-03
NMVOC, non-methane volatile organic compounds, unspecified origin	4.48E-03
Organic substances, unspecified	6.40E-05
Particulates	2.31E-06
Particulates, < 10 um	1.54E-04
Particulates, < 2.5 um	5.51E-04
Particulates, > 10 um	4.28E-04
Particulates, > 2.5 um, and < 10um	2.17E-04
Particulates, unspecified	2.11E-04
Pentane	1.63E-05
Propane	2.87E-06
Sodium	3.52E-06
Sulfur dioxide	2.99E-04
Sulfur oxides	1.44E-02
Toluene	2.85E-06
Vanadium	1.22E-05
VOC, volatile organic compounds	5.14E-05
Water	6.53E-06
	MJ/kg resin
Heat, waste	2.21E+01
	Bq/kg resin
Noble gases, radioactive, unspecified	1.42E+02
Radioactive species, unspecified	3.24E+03
Radon-222	2.71E+02

Emissions to water	**kg/kg resin**
Aluminum	3.54E-06
Ammonia, as N	1.21E-04
Ammonium, ion	1.71E-04
BOD5, Biological Oxygen Demand	7.03E-04
Boron	6.95E-06
Calcium, ion	3.20E-05
Chloride	1.01E-03
COD, Chemical Oxygen Demand	3.87E-04
DOC, Dissolved Organic Carbon	8.91E-05
Formaldehyde	1.04E-04
Iron	9.30E-06
Iron, ion	4.89E-06
Lead	6.08E-08
Manganese	5.34E-06
Mercury	2.82E-10
Metallic ions, unspecified	3.32E-06
Methanol	9.30E-06
Nickel, ion	1.40E-06
Nitrogen	5.78E-05
Oils, unspecified	3.64E-04
Organic substances, unspecified	5.94E-05
Phenol	3.11E-06
Phosphorus	3.10E-06
Silicon	3.41E-04
Sodium, ion	2.89E-05
Solids, inorganic	2.24E-04
Solved solids	2.04E-02
Sulfate	8.49E-04
Sulfuric acid	1.73E-06
Suspended solids, unspecified	6.63E-04
	MJ/kg resin
Heat, waste	1.26E-01
	Bq/kg resin
Hydrogen-3, Tritium	6.33E+00

Emissions to land	**kg/kg resin**
Oils, unspecified	1.24E-06
Solids	2.23E-04
Waste, solid	6.75E-02

2.6 Cradle-to-Product Gate Resource Use for Embodied Energy

The embodied energy to produce UF resin can be given in several formats. For this study it is useful to examine the energy breakdown in terms of both its source of fuel and feedstock in the ground and its contribution by the various input substances and processes. The natural gas and crude oil feedstock to produce chemicals were considered in terms of their higher heating values along with the energy of the various fuels.

Table 2.8 gives the cumulative energy equivalent from cradle-to-product gate for the production of UF resin in terms of its fuel and feedstock source in the ground. To produce 1.0 kg of resin it takes a total of 29.35 MJ of embodied energy based on the higher heating values of the various fuels and feedstock.

Natural gas provides 71% of the energy, followed by crude oil at 22%, coal at 6.1%; and all other sources are of minor significance. As expected the natural gas use is high since it is not only used as fuel for processing and electricity, it is a source of feedstock for the primary input chemicals.

Table 2.8. Cradle-to-gate fuel and electricity use in terms of their energy equivalence for the manufacture of 1.0 kg of UF resin at 65% non-volatile solids.

Energy use by fuel source	Energy[1] MJ/kg resin	Contribution %
Coal in ground	1.79E+00	6.1
Crude oil in ground	6.47E+00	22.0
Natural gas in ground	2.09E+01	71.1
Uranium in ground	1.17E-01	0.4
Wood fuel	1.48E-03	0.0
Electricity from other gases	3.55E-03	0.0
Electricity from other renewables	2.04E-02	0.1
Energy, from hydro power	6.04E-02	0.2
Energy, potential (in hydropower reservoir), converted	7.86E-03	0.0
TOTAL	29.35	100.0

[1] Electricity at 3.6 MJ/kWh, uranium at 381,000 MJ/kg and other fuels at their higher heating value (HHV) of coal 26.2 MJ/kg, crude oil 45.5 MJ/kg, natural gas 54.4 MJ/kg, and wood 20.9 MJ/kg.

Energy equivalence by the input chemicals and process component to manufacturing can be of value in assessing the major contributors and for identifying opportunities for reducing energy use. Table 2.9 gives the embodied energy breakdown for manufacturing UF resin from in-ground resource to the output gate of the resin plant. The total energy is 29.35 MJ/kg resin with the urea and the methanol providing the major contributions of 58.9% and 37.5% respectively due to their manufacture, all other contributors are of lesser significance. Transportation of chemical inputs to the plant represents only 1.0% of the total energy. Energy to provide resin manufacturing process energy and electricity for heat and emissions control represents only 2.44% of the total.

Table 2.9. A breakdown of energy contributors to produce UF resin cradle-to-product gate (based on HHV of fuel).

Energy use by process component	Energy MJ/kg resin	Contribution %
Urea	1.73E+01	58.9
Methanol	1.10E+01	37.6
Formic acid 10% solids	3.45E-02	0.12
Ammonium sulfate 20% solids	1.24E-03	0.00
Sodium hydroxide 50% solids	8.22E-03	0.03
Trailer diesel	3.25E-02	0.11
Diesel locomotive	2.61E-01	0.89
Natural gas	3.74E-01	1.3
Natural gas equipment (surrogate propane)	4.80E-07	0.00
Electricity, USA average process	1.93E-01	0.66
Electricity, USA average emissions equipment	1.49E-01	0.51
TOTAL	29.35	100

2.7 Sensitivity Analysis

The sensitivity analysis involves examining the impact of varying an input parameter such as fuel to a process and examining the magnitude of the change of a LCI output parameter such as resource use or carbon dioxide (fossil) emission. The magnitude of the impact is dependent on the input parameter and also on the output parameter of interest. Table 2.10 and 2.11 show that the dominant contributors are input materials of urea and methanol with little if any contributions from on-site inputs of other chemicals, fuel, and electricity, and little if any contribution by transportation of chemicals to the resin plant. As such, changing the two dominant parameters will have a significant impact on most resource use and emissions whereas changes of lesser contributing parameters such as transportation fuels, plant input chemicals of formic acid, ammonium sulfate, sodium hydroxide, and on-site use of natural gas and electricity will have little if any impact. As an example to show that the impact is proportional to the change of the major contributors, even though it would not be practical commercially to do so, input of urea to the process was increased by 10% giving the outputs shown in Table 2.12 comparing selected resources and emissions to the base case. As expected the outputs varied proportionately to the contribution of the base case for a given resource use or emission. The change varies from 0% to an expected maximum of 10% for those substances that urea is the sole contributor.

This exercise was hypothetical in that actually varying the content significantly for either the urea or methanol is not practical since the manufacturers are producing the resin to specific criteria but this example does show expected results of a sensitivity study.

Table 2.10. Contribution by input parameter to use of raw materials for the manufacture of UF resin.

			Process input chemicals					Transportation		UF process	
Substance		UF resin process	Urea	Methanol	Formic acid	Ammonium sulfate	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
	kg/kg resin	% contribution									
Aluminium, 24% in bauxite, 11% in crude ore, in ground	4.69E-05	0	4	96	0	0	0	0	0	0	0
Barite, 15% in crude ore, in ground	1.33E-06	0	1	25	0	0	75	0	0	0	0
Calcite, in ground	9.66E-04	0	92	5	0	0	2	0	0	0	0
Carbon dioxide, in air	2.74E-05	0	42	21	35	0	2	0	0	0	0
Clay, unspecified, in ground	2.02E-04	0	93	7	0	0	0	0	0	0	0
Coal, 26.4 MJ per kg, in ground	6.79E-02	0	76	11	0	0	0	0	0	0	12
Coal, brown, in ground	1.88E-04	0	5	23	70	0	2	0	0	0	0
Coal, hard, unspecified, in ground	1.53E-04	0	21	29	47	0	3	0	0	0	0
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.04E-06	0	0	100	0	0	0	0	0	0	0
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	5.79E-06	0	0	100	0	0	0	0	0	0	0
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.53E-06	0	0	100	0	0	0	0	0	0	0
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	7.61E-06	0	0	100	0	0	0	0	0	0	0
Fluorspar, 92%, in ground	1.62E-06	0	83	16	1	0	0	0	0	0	0
Gas, mine, off-gas, process, coal mining/m3	1.15E-06	0	28	27	43	0	3	0	0	0	0
Gas, natural, 46.8 MJ per kg, in ground	3.84E-01	0	46	51	0	0	0	0	0	2	0
Gas, natural, in ground	7.83E-05	0	35	26	37	0	1	0	0	0	0
Gravel, in ground	7.72E-03	0	96	4	0	0	0	0	0	0	0
Iron, 46% in ore, 25% in crude ore, in ground	8.35E-06	0	3	97	0	0	0	0	0	0	0
Limestone, in ground	3.92E-03	0	76	11	0	0	0	0	0	0	12
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in grd	3.00E-06	0	0	100	0	0	0	0	0	0	0
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in grd	6.05E-06	0	0	100	0	0	0	0	0	0	0
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.63E-04	0	97	3	0	0	0	0	0	0	0
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.30E-06	0	0	3	0	0	0	0	0	0	0
Oil, crude, 42 MJ per kg, in ground	1.42E-01	0	94	2	0	0	0	0	4	0	0
Oil, crude, in ground	3.06E-04	0	16	13	70	0	0	0	0	0	0
Sodium chloride, in ground	4.76E-04	0	1	19	0	0	80	0	0	0	0
Uranium, 2291 GJ per kg, in ground	2.90E-07	0	77	11	0	0	0	0	0	0	12
Uranium, in ground	8.45E-09	0	15	21	61	0	2	0	0	0	0
Water, cooling, unspecified natural origin/m3	2.76E+00	0	0	92	7	0	1	0	0	0	0
Water, lake	9.40E-05	0	80	14	5	0	0	0	0	0	0
Water, process, drinking	2.93E-01	0	0	100	0	0	0	0	0	0	0
Water, process, unspecified natural origin/kg	4.20E-01	100	0	0	0	0	0	0	0	0	0
Water, process, well, in ground	8.00E-02	100	0	0	0	0	0	0	0	0	0
Water, river	1.29E-02	0	49	32	19	0	1	0	0	0	0
Water, salt, ocean	6.62E-04	0	13	21	64	0	2	0	0	0	0
Water, salt, sole	2.23E-04	0	11	12	77	0	0	0	0	0	0
Water, unspecified natural origin/m3	6.52E-01	0	99	0	0	0	0	0	0	0	0
Water, well, in ground	3.45E-02	0	94	4	2	0	0	0	0	0	0
Wood and wood waste, 9.5 MJ per kg	2.83E-04	0	67	29	0	0	0	0	1	1	2
Wood, hard, standing	2.06E-06	0	16	26	56	0	2	0	0	0	0
Wood, primary forest, standing	2.08E-09	0	73	21	5	0	1	0	0	0	0
Wood, soft, standing	1.15E-05	0	52	20	27	0	2	0	0	0	0
Wood, unspecified, standing/m3	5.82E-10	0	96	4	0	0	0	0	0	0	0
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	1.11E-05	0	0	100	0	0	0	0	0	0	0

Table 2.11. Contribution by input parameter to air emissions for the manufacture of UF resin.

			Process input chemicals					Transportation		UF process	
Emissions to air		**UF resin**	**Urea**	**Methanol**	**Formic acid**	**Ammonium sulfate**	**Sodium hydroxide**	**Diesel truck**	**Diesel rail**	**Natural gas**	**Electricity**
	kg/kg resin	**% contribution**									
Acetic acid	4.84E-06	0	100	0	0	0	0	0	0	0	0
Aldehydes, unspecified	1.93E-05	0	69	6	0	0	0	3	21	0	0
Aluminum	4.56E-06	0	87	12	0	0	0	0	0	0	0
Ammonia	1.64E-03	0	100	0	0	0	0	0	0	0	0
Benzene	5.43E-06	0	100	0	0	0	0	0	0	0	0
Butane	9.50E-06	0	100	0	0	0	0	0	0	0	0
Carbon dioxide, biogenic	4.53E-04	0	57	37	2	0	0	0	1	1	2
Carbon dioxide, fossil	1.52E+00	0	84	12	0	0	0	0	1	1	1
Carbon disulfide	1.92E-06	0	84	16	0	0	0	0	0	0	0
Carbon monoxide	2.03E-03	0	51	41	0	0	0	1	5	2	1
Carbon monoxide, fossil	1.40E-03	0	100	0	0	0	0	0	0	0	0
Dimethyl ether	2.18E-05	100	0	0	0	0	0	0	0	0	0
Dinitrogen monoxide	1.04E-05	0	96	2	0	0	0	0	0	0	2
Ethanol	1.41E-06	0	100	0	0	0	0	0	0	0	0
Formaldehyde	1.13E-05	68	32	0	0	0	0	0	0	0	0
Hydrocarbons, aliphatic, alkanes, unspecified	2.82E-06	0	100	0	0	0	0	0	0	0	0
Hydrogen chloride	1.91E-05	0	85	7	0	0	0	0	0	0	7
Hydrogen fluoride	2.38E-06	0	83	8	0	0	0	0	0	0	8
Mercury	6.77E-09	0	79	11	0	0	0	0	0	0	9
Methane	2.82E-03	0	50	47	0	0	0	0	0	2	2
Methane, biogenic	2.41E-06	0	99	0	0	0	0	0	0	0	0
Methane, fossil	6.81E-04	0	55	45	0	0	0	0	0	0	0
Methanol	1.73E-04	3	1	95	0	0	0	0	0	0	0
Methyl formate	1.25E-06	0	0	0	100	0	0	0	0	0	0
Nickel	3.24E-06	0	99	1	0	0	0	0	0	0	0
Nitrogen oxides	3.40E-03	0	66	24	0	0	0	1	6	1	2
NMVOC, non-methane volatile organic compounds, unspecified origin	4.48E-03	0	55	40	0	0	0	0	2	1	0
Organic substances, unspecified	6.40E-05	0	72	5	0	0	0	16	8	0	0
Particulates	2.31E-06	100	0	0	0	0	0	0	0	0	0
Particulates, < 10 um	1.54E-04	0	54	8	0	0	0	2	33	1	3
Particulates, < 2.5 um	5.51E-04	0	100	0	0	0	0	0	0	0	0
Particulates, > 10 um	4.28E-04	0	100	0	0	0	0	0	0	0	0
Particulates, > 2.5 um, and < 10um	2.17E-04	0	100	0	0	0	0	0	0	0	0
Particulates, unspecified	2.11E-04	0	76	13	0	0	0	0	1	0	10
Pentane	1.63E-05	0	100	0	0	0	0	0	0	0	0
Propane	2.87E-06	0	99	0	1	0	0	0	0	0	0
Sodium	3.52E-06	0	100	0	0	0	0	0	0	0	0
Sulfur dioxide	2.99E-04	0	94	5	1	0	0	0	0	0	0
Sulfur oxides	1.44E-02	0	49	48	0	0	0	0	0	2	1
Toluene	2.85E-06	0	100	0	0	0	0	0	0	0	0
Vanadium	1.22E-05	0	100	0	0	0	0	0	0	0	0
VOC, volatile organic compounds	5.14E-05	100	0	0	0	0	0	0	0	0	0
Water	6.53E-06	0	87	13	0	0	0	0	0	0	0

Table 2.12. Contribution by input parameter to air emissions for the manufacture of UF resin comparing the base case to a 10% increase of urea input.

Raw material	UF base case kg/kg resin	UF base+10% urea kg/kg resin	Change %
Aluminium, 24% in bauxite, 11% in crude ore, in ground	4.69E-05	4.71E-05	0
Barite, 15% in crude ore, in ground	1.33E-06	1.33E-06	0
Calcite, in ground	9.66E-04	1.06E-03	9
Carbon dioxide, in air	2.74E-05	2.85E-05	4
Clay, unspecified, in ground	2.02E-04	2.21E-04	9
Coal, 26.4 MJ per kg, in ground	6.79E-02	7.31E-02	8
Coal, brown, in ground	1.88E-04	1.89E-04	1
Coal, hard, unspecified, in ground	1.53E-04	1.56E-04	2
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.04E-06	1.04E-06	0
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	5.79E-06	5.79E-06	0
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.53E-06	1.54E-06	0
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	7.61E-06	7.61E-06	0
Fluorspar, 92%, in ground	1.62E-06	1.75E-06	8
Gas, mine, off-gas, process, coal mining/m3	1.15E-06	1.18E-06	3
Gas, natural, 46.8 MJ per kg, in ground	3.84E-01	4.02E-01	5
Gas, natural, in ground	7.83E-05	8.11E-05	4
Gravel, in ground	7.72E-03	8.46E-03	10
Iron, 46% in ore, 25% in crude ore, in ground	8.35E-06	8.37E-06	0
Limestone, in ground	3.92E-03	4.21E-03	8
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	3.00E-06	3.00E-06	0
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	6.05E-06	6.05E-06	0
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.63E-04	2.88E-04	10
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.30E-06	1.30E-06	0
Oil, crude, 42 MJ per kg, in ground	1.42E-01	1.55E-01	9
Oil, crude, in ground	3.06E-04	3.11E-04	2
Sodium chloride, in ground	4.76E-04	4.77E-04	0
Uranium, 2291 GJ per kg, in ground	2.90E-07	3.12E-07	8
Uranium, in ground	8.45E-09	8.58E-09	2
Water, cooling, unspecified natural origin/m3	2.76E+00	2.76E+00	0
Water, lake	9.40E-05	1.02E-04	8
Water, process, drinking	2.93E-01	2.93E-01	0
Water, process, unspecified natural origin/kg	4.20E-01	4.20E-01	0
Water, process, well, in ground	8.00E-02	8.00E-02	0
Water, river	1.29E-02	1.35E-02	5
Water, salt, ocean	6.62E-04	6.71E-04	1
Water, salt, sole	2.23E-04	2.25E-04	1
Water, unspecified natural origin/m3	6.52E-01	7.16E-01	10
Water, well, in ground	3.45E-02	3.78E-02	9
Wood and wood waste, 9.5 MJ per kg	2.83E-04	3.02E-04	7
Wood, hard, standing	2.06E-06	2.09E-06	2
Wood, soft, standing	1.15E-05	1.21E-05	5
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	1.11E-05	1.11E-05	0

Table 2.13. Contribution by input parameter to air emissions for the manufacture of UF resin comparing the base case to a 10% increase of urea input.

Emissions to air	UF base case kg/kg resin	UF base+10% urea kg/kg resin	Change %
Acetic acid	4.84E-06	5.33E-06	10
Aldehydes, unspecified	1.93E-05	2.07E-05	7
Aluminum	4.56E-06	4.96E-06	9
Ammonia	1.64E-03	1.80E-03	10
Benzene	5.43E-06	5.97E-06	10
Butane	9.50E-06	1.04E-05	10
Carbon dioxide, biogenic	4.53E-04	4.79E-04	6
Carbon dioxide, fossil	1.52E+00	1.64E+00	8
Carbon disulfide	1.92E-06	2.08E-06	8
Carbon monoxide	2.03E-03	2.13E-03	5
Carbon monoxide, fossil	1.40E-03	1.54E-03	10
Dimethyl ether	2.18E-05	2.18E-05	0
Dinitrogen monoxide	1.04E-05	1.14E-05	10
Ethanol	1.41E-06	1.55E-06	10
Formaldehyde	1.13E-05	1.14E-05	3
Hydrocarbons, aliphatic, alkanes, unspecified	2.82E-06	3.10E-06	10
Hydrogen chloride	1.91E-05	2.07E-05	8
Hydrogen fluoride	2.38E-06	2.58E-06	8
Mercury	6.77E-09	7.30E-09	8
Methane	2.82E-03	2.97E-03	5
Methane, biogenic	2.41E-06	2.64E-06	10
Methane, fossil	6.81E-04	7.19E-04	6
Methanol	1.73E-04	1.73E-04	0
Methyl formate	1.25E-06	1.25E-06	0
Nickel	3.24E-06	3.56E-06	10
Nitrogen oxides	3.40E-03	3.63E-03	7
NMVOC, non-methane volatile organic compounds, unspecified origin	4.48E-03	4.73E-03	6
Organic substances, unspecified	6.40E-05	6.86E-05	7
Particulates	2.31E-06	2.31E-06	0
Particulates, < 10 um	1.54E-04	1.62E-04	5
Particulates, < 2.5 um	5.51E-04	6.06E-04	10
Particulates, > 10 um	4.28E-04	4.71E-04	10
Particulates, > 2.5 um, and < 10um	2.17E-04	2.39E-04	10
Particulates, unspecified	2.11E-04	2.27E-04	8
Pentane	1.63E-05	1.79E-05	10
Propane	2.87E-06	3.15E-06	10
Sodium	3.52E-06	3.87E-06	10
Sulfur dioxide	2.99E-04	3.27E-04	9
Sulfur oxides	1.44E-02	1.51E-02	5
Toluene	2.85E-06	3.13E-06	10
Vanadium	1.22E-05	1.34E-05	10
VOC, volatile organic compounds	5.14E-05	4.95E-05	0
Water	6.53E-06	7.10E-06	9

2.8 Carbon Content and Footprint of UF Resin

When it comes to climate change and related issues as a result of increased greenhouse gas emissions to the atmosphere, two topics are of interest: 1) the amount of carbon store in a material that can in some instances be considered as an offset when sequestered near-term to reduce the amount of CO_2 emissions to the atmosphere, and 2) the carbon footprint of a material that gives the amount of greenhouse gases such as CO_2 released to the atmosphere during its life cycle. The sum of the two values with carbon store as a negative value gives the net CO_2 impact of a material upon the environment.

Cured UF resin is comprised of 25.4% of carbon by weight for 0.254 kg/kg resin 100% solids (Broline 2008). The percentage is based on in-mill additives and no loss of formaldehyde. The carbon content is an estimate which can vary with changes in formulation and resin mix. Unfortunately this carbon cannot be considered as a carbon store offset to CO_2 emissions since it is not continuously renewing in the carbon cycle. The resin carbon was sequestered hundreds of million years ago during the formation of the fossil fuels that are used as their feedstock. The carbon in resins is unlike the carbon stored in trees and wood which was sequestered near-term of only 30-100 years ago, is part of a continuously renewing carbon cycle, and can be counted as an offset against emissions of CO_2 to the atmosphere when looking at a materials carbon footprint and impact upon global warming.

The carbon footprint for the production of UF resin is determined by the CO_2 equivalent of all greenhouse gas (GHG) emissions during its life cycle, in this case from resources in the ground through extraction, deliveries and manufacturing of the liquid resin. The CO_2 equivalent of each GHG can be determined by multiplying its comparative reactive factor in the atmosphere to that for carbon dioxide based on a 100-year time horizon (IPCC 2007). There are three GHGs that normally occur for the life cycle of wood products—CO_2, CH_4 (methane), and N_2O (listed as nitrous oxide and dinitrogen oxide in the LCI output). The total carbon footprint for the life cycle of UF resin cradle-to-gate is given by the following equation—the values of each contribution are given in Table 2.6:

Carbon Footprint kg-CO_2 eq = CO_2 kg + (CH_4 kg x 25) + (N_2O kg x 298)

The carbon footprint in kg-CO_2 equivalent (eq) is determined by the mass of each contributor times how reactive it is in comparison to CO_2 in the atmosphere, e.g., CH_4 is 25 times more reactive than CO_2 and N_2O is 298 times more reactive than CO_2. Considering the total emissions from cradle-to-product gate for each of these contributors gives a total of 2.474 kg-CO_2 eq per kg of 100% solids UF resin, see Table 2.14. These emissions are generated in the process of extracting the fuel, generation of electricity, delivery of fuel, and the combustion fuel in the manufacture of the resin.

Table 2.14. The carbon footprint given in kg-CO2 equivalent (eq) for 100% solids UF resin.

Greenhouse gas (GHG)	GHG Contribution kg/kg resin 65% solids	CO_2 equiv. multiplier	Carbon Footprint kg-CO_2 eq/kg resin 100% solids
CO_2	1.5173	1	2.3343
Methane (CH_4)	0.00351	25	0.1349
Nitrous oxide (N_2O)	0.0000104	298	0.0048
Total			2.4740

2.9 Study Discussion

The data documented in this report on the manufacture of UF resin forms a foundation for the scientific assessment of its environmental performance. The UF resin data should not be considered as a stand alone product; rather it should be used when conducting life-cycle inventories and assessments of wood composite products that use this resin as a bonding agent during their manufacture. Resins are an integral component and contributor to the performance of wood composites. A life-cycle assessment of the use of resins in composites can be used in a number of ways to show their favorable performance for such environmental issues as sustainability, global warming, climate change, carbon footprint, carbon storage, carbon trading and caps, carbon taxes, green purchasing, and green building. The data can be used as stated or in a life-cycle assessment to compare wood composite products to various competitive materials or assemblies of various materials. Individual LCI data of UF resin can be used as a benchmark for process or product improvements or for comparing performance to those of other materials.

2.10 Conclusion

A cradle-to-product gate life-cycle inventory (LCI) study was conducted of manufacturing 1.0 kg of urea formaldehyde (UF) resin at 65% solids—the LCI functional unit for this study—in the U.S. The study covered data analyses from the raw resources in the ground through resin manufacturing for the production year 2005. Production data were collected by survey of resin manufacturers representing 72% of total U.S. production of UF resin for the particleboard, MDF, and hardwood plywood industries that annually used about 1,226,000,000 kg of UF resin at 65% non-volatile solids. Secondary LCI data from the Franklin Associates Limited and Ecoinvent databases were used for input chemicals, fuels, electricity and transportation.

The quality of the LCI data collected for the manufacture of UF resin was high as judged by assessments for similarity of values, molar ratio of formaldehyde to urea, and the mass flows of materials into and out of the process. Any data questions were resolved by re-contacting the manufacturers that participated in the survey. The molar ratio of formaldehyde to urea was found to be 1.09 as expected.

Assigning of environmental burden in the production of UF resin was entirely to the product since no co-products are produced during the process. Of the output functional unit of 1.0 kg of UF resin at 65% solids, the main input components on a dry solids basis were urea at 0.473 kg and methanol at 0.309 kg; water at 0.499 kg for resin and processing; and a number of lesser significant quantities of acids and caustics were used throughout the process. The methanol is used in reactors to produce formaldehyde which is then used with the addition of urea in another reactor to produce the UF resin.

Environmental impacts were assessed for those at the resin manufacturing site (referred to as on-site emissions) and those for cradle-to-product gate which begins with resources in the ground through extraction, generation, delivery, and resin manufacture. On-site impacts are generally small compared to the cradle-to-gate impacts. Per 1.0 kg of liquid resin the on-site energy use is 0.394 MJ compared to 29.35 MJ/kg resin for cradle-to-product gate, and emissions to air such as CO_2, CO, VOCs, particulate, formaldehyde and methanol are 1%, 1%, 100%, 1%, 69% and 3% for the on-site compared to the cradle-to-gate values. The on-site VOC emissions are high because the LCI databases used for input chemicals, fuels and electricity list individual VOC emissions and not the grouping like was done for the on-site data, and the formaldehyde is high because it occurred due to the on-site manufacture of formaldehyde and the UF resin. The on-site emissions to water and land are also much smaller. Overall the resin operations are resource efficient and relatively friendly to the environment.

In terms of energy equivalent for fuels and feedstock from cradle-to-product gate, the manufacture of urea and methanol from in-ground fuel resources contributed to 58.9% and 37.6% respectively of the total energy. The transportation of chemical inputs to the resin plants, and on-site processing fuels and electricity were all minor contributors to the total energy.

A sensitivity of the input parameters to the output use of materials and emissions to air, water, and land were likewise dominated by input urea and methanol chemicals. Other inputs of on-site fuel and electricity use, and transportation of chemicals to the plant, all were minor contributors. Increasing urea by a percentage resulted in expected proportional outputs of emissions where urea was a dominant contributor; similar changes to methanol input would lead to proportional changes in emissions; whereas changes for lesser input chemical and processes like electricity generally resulted in no significant changes in output.

The carbon footprint from cradle-to-gate to produce UF resin is 2.474 kg-CO_2 eq per 1.0 kg of 100% solids resin. The carbon footprint accounts for all greenhouse gas emissions during the life cycle of a product, in this case from cradle-to-gate. Although UF cured resin has a carbon component of about 25%, it is not considered as an offset for CO_2 emissions to the atmosphere during processing since its carbon was not sequestered near-term and it is not a continuously renewing carbon cycle.

To benefit from the availability of a LCI database for UF resin, the following additional studies are recommended: 1) extract pertinent data that documents the favorable environmental performance of UF resin and 2) edit prior CORRIM LCI studies that used UF resin to include the LCI data developed in this study.

3.0 Life-Cycle Inventory of Melamine-Urea-Formaldehyde Resin

3.1 Introduction

3.1.1 Survey Data

The melamine-urea-formaldehyde (MUF) resin survey data were for 6 plants in U.S. that represented 77% of total production for the year 2005. Total annual production was 190,893,000 lbs (86,588,000 kg) of neat resin at 60% non-volatile solids content. MUF production is small compared to UF resin; it is only 8% or less of UF annual production. MUF production is estimated for the particleboard and MDF industries.

3.1.2 Materials Flow

Those materials considered in the LCI analysis of MUF resin production included those listed in Table 3.1. The process is essentially identical to the production of UF resin with the exception that a small portion of melamine, about 8% by weight (the industry average for this study) on a neat resin basis, is substituted for a portion of the urea input. There are two types of MUF resin, those in which a small amount of melamine is added to improve the performance of commodity resins and those in which a larger amount is added to provide some moisture resistant properties. The more melamine used in the formulation the greater the water resistance of the cured resin; low water resistance MUF resins have a substitution of about 2% and high water resistance resins would be about 10% based on the liquid resin weight. Input materials considered were melamine, urea, methanol, formic acid, ammonium sulfate, sodium hydroxide, and water. Other chemicals of minor contribution are used and were not included in the analysis since their total was much less than 1% weight of resin. The silver or molybdenum/iron oxide catalyst used to produce formaldehyde from methanol was not included in the analysis because it too is a small contributor to the analysis and the manufacturers considered this information proprietary.

Table 3.1. Listing of input chemicals used to produce melamine-urea-formaldehyde (MUF) resin.

Input Material	Product
Melamine (100%)[1]	MUF resin (60%)[2]
Urea (100%)	
Methanol (100%)	
Formic acid (10%)	
Ammonium sulfate (20%)	
Sodium hydroxide (50%)	
Water	

[1] Solids content or solution strength of chemicals into the plant.

[2] Solids content of resin out of the plant.

3.1.3 Transportation

The delivery of chemicals to the resin plants is by both truck and rail. Table 3.2 gives the one-way deliver distances. Usually the truck deliveries have no back haul of other materials. The t•km (the mass (t for tonne) times distance traveled (km)) values are used in the SimaPro software by accessing the FAL database to obtain U.S. typical environmental impacts for truck and rail transportation. Other chemicals are used in the resin production process but their quantity and contribution to environmental impacts were so insignificant that they were not included in either the input data or the transportation calculations.

Table 3.2. One-way delivery distance for input chemicals to MUF resin plants.

	Transportation		One-way distance	Chemical weight		Truck	Rail
Chemical	mode	% mode	km	kg	t	tkm	tkm
Urea	truck	14	123	0.397	3.97E-04	6.84E-03	
Urea	rail	86	792	0.397	3.97E-04		2.70E-01
Melamine	truck	100	1,989	0.081	8.10E-05	1.61E-01	
Melamine	rail	0	0	0.081			
Methanol	truck	16	260	0.304	3.04E-04	1.26E-02	
Methanol	rail	84	1,990	0.304	3.04E-04		5.08E-01
Formic acid	truck	100	347	5.09E-04	5.09E-07	1.77E-04	
Ammonium sulfate	truck	100	347	1.47E-04	1.47E-07	5.10E-05	
Ammonium sulfate	rail	0					
Sodium hydroxide	truck	100	347	4.18E-04	4.18E-07	1.45E-04	
Sodium hydroxide	rail	0		.			
Total						1.81E-01	7.79E-01

3.2 Product Yields

The inputs to produce 1.0 kg of neat melamine-urea-formaldehyde (MUF) resin at 60% non-volatile solids content consist of three primary chemicals on a dry basis of melamine at 0.081 kg, urea at 0.397 kg and methanol at 0.304 kg, much lesser amounts of formic acid, ammonium sulfate, and sodium hydroxide, and 0.791 kg of water. A significant portion of the processing water is recycled back into the resin. See Table 3.3 for all inputs and outputs, except emissions, for the manufacture of MUF resin. Electricity is used for processing by fans and pumps, and for operating emissions control equipment, while the natural gas is used for boiler fuel and emission control equipment, and propane is used for fuel in forklifts.

Table 3.3. Inputs for the production of 1.0 kg of MUF resin at 60% solids.

	SI unit	Unit/kg MUF 60% solids
INPUTS		
Chemicals[1]		
Melamine	kg	8.08E-02
Urea	kg	3.97E-01
Methanol	kg	3.04E-01
Formic acid	kg	5.09E-05
Ammonium sulfate	kg	2.94E-05
Sodium hydroxide	kg	2.09E-04
Water[2]		
Water for producing MUF resin	kg	1.27E-01
Water use; cooling tower	kg	5.79E-01
Water other; boiler makeup water	kg	8.50E-02
Electricity and fuel use		
Electricity	kWh	2.09E-02
Electricity emissions control	kWh	1.42E-02
Natural gas used in boiler	m^3	1.35E-02
Propane	L	1.55E-05
OUTPUTS[3]		
MUF liquid resin (60%)	kg	1.0

[1] All chemical weights given at either 100% non-volatile solids or dry except for MUF resin given on a 60% solids basis.

[2] There is a significant amount of water recycling back into the resin.

[3] Emissions to air, water and land listed in separate table.

The molar ratio of formaldehyde to urea plus melamine was used as a check on the quality of the data. Assuming that it takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde, the molar ratio of formaldehyde to urea plus melamine for this representative resin system was determined to be 1.16 which is in the expected range of 1.15 to 1.30 for a contemporary commercial MUF resin for use in the particleboard and MDF industries. The value of the molar ratio affects both the performance of the resin and the properties of the composite panel made with this resin. The value of the molar ratio also affects the moisture resistance of the cured resin, with higher values being more resistant.

3.3 Manufacturing Energy Summary

3.3.1 Sources of Energy and Electricity

Energy for the production of MUF resin comes from electricity to operate fans and pumps, natural gas to generate steam (boiler) for heating reactors and input chemicals, and propane gas (LPG) to operate forklift equipment. Electricity and natural gas are also used to operate regenerative thermal oxidizers (RTOs) and regenerative catalytic oxidizers (RCOs) at some plants to control air emissions. A breakdown by fuel source for the production of electricity for the U.S. in 2005 was given previously in Table 1.1.

Natural gas is the primary fuel in resin manufacturing; it is used for generating steam that is used to heat input chemicals and reactors; and is used for combusting VOCs and HAPs in RTO and RCO emission control systems. The natural gas and/or electricity use would have been greater had all resin plants used RTO and RCO emissions control devices. In addition to natural gas use, a small amount of propane fuel was used to operate fork lift trucks and handlers within the plant. Table 3.4 gives the energy use on-site for manufacturing MUF resin. The natural gas provides 80.3% of the energy and the electricity provides 19.6%. The propane is an insignificant contributor to the energy use.

Table 3.4. On-site fuel and electricity use in terms of their energy equivalence for the manufacture of 1.0 kg of MUF resin at 60% non-volatile solids.

Energy use[1]	Unit	Unit/kg MUF resin	MJ/kg MUF resin	% Use
Electricity process	MJ	7.53E-02	7.53E-02	11.7
Electricity emissions control	MJ	5.11E-02	5.11E-02	7.9
Natural gas	m^3	1.35E-02	5.17E-01	80.3
Propane	L	1.55E-05	5.89E-07	0.0
Total energy			6.43E-01	100

[1] Electricity at 3.6 MJ/kWh and fuels at their higher heating value (HHV) of natural gas at 54.4 MJ/kg and propane at 54.0 MJ/kg.

3.4 Plant Emissions for Producing MUF Resin

Outputs for the production of 1.0 kg of MUF resin at 60% solids include emissions to air, water and land, see Table 3.5. Emissions are generated due to emissions from the combustion of gases and the chemical reactions in the reactors. For combustion, only CO_2 and CO are given—both were calculated using the SimaPro software, actual natural gas use, and the FAL database for U.S. fuels—the total emissions are determined by considering natural gas and propane on-site fuel use. All other emissions were collected by survey; they include emissions to air of particulate, volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) of formaldehyde and methanol that come off of the absorber and the reactor. The dimethyl ether emissions occur for the molybdenum/iron oxide process and not at any measurable amounts for the silver oxide process in the production of formaldehyde. Emissions to water include biological chemical demand (BOD), total suspended solids (TSS), solids, ammonia nitrogen (NH_3N) and formaldehyde (HCHO).

Table 3.5. On-site reported outputs for the production of 1.0 kg of MUF resin at 60% non-volatile solids.

	Survey Wt. Average kg/kg MUF 60% solids
Production output	
MUF resin (60% solids)	1.00
Emissions to air[1]	
CO_2[2], fossil (GHG)[3]	2.55E-02
CO[2]	1.30E-05
VOC	4.94E-05
Particulate	1.65E-06
Formaldehyde (HAP)[3]	7.85E-06
Methanol (HAP)[3]	5.49E-06
Dimethyl ether	2.26E-05
Emissions to water[1]	
BOD	6.62E-04
TSS	3.94E-04
Solids	2.39E-04
Ammonia nitrogen (NH_3N)	1.30E-04
Formaldehyde (HCHO)	7.84E-05
Emissions to land[1]	
Solids	5.09E-05

[1] Emissions data reported in survey.

[2] CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant.

[3] HAP hazardous air pollutant; GHG greenhouse gas.

3.5 Cradle-to-Product Gate Process Related Resource Use and Emissions

The life-cycle inventory for the production of MUF resin covers its cycle from in-ground resources through the production and delivery of input chemicals and fuels, through its manufacture of a resin as shipped to the customer. It examines the use of all resources, fuels and electricity and all emissions to air, water and land; it also includes feedstock of natural gas and crude oil used to produce some of the chemicals. Table 3.6 gives the raw materials and energy sources, and Table 3.7 gives emissions to air, water and land for the cradle-to-gate inventory. The raw materials in the ground include coal, natural gas, limestone, crude oil, and uranium, water usage and others. Materials of quantities smaller than 1.0E-06 kg/kg are not included in the listing. Because life-cycle studies involve tracing resource use back to its in-ground resources, some materials or substances can involve many steps of backtracking to their source, resulting in the use of a large numbers of substances, many of insignificant quantity. For this study a filter was used to remove insignificant substances from the listing. The filter varied depending on whether the emission was to air, water or land. The exception was for substances that are highly toxic such as uranium and mercury due to the production of electricity where values less than the cut-off value are shown.

Some sources of energy or fuels cannot be traced back to their original resource in the ground. Such energies include "energy from hydro power," "electricity from other gases" and "electricity from renewables" which are not defined in terms of identifiable fuels are listed in a separate category defined as Energy and are given in MJ/kg of resin.

Emissions for the cradle-to-gate scenario are listed in Table 3.7. The emissions to air and water used a cut-off value of 1.0E-06 kg/kg resin, and radiation type emissions had a cut-off of 1.0E+00 Bq/kg resin. Emissions to land used a cut-off of 1.0E-06 kg/kg resin. Some emissions because of their toxicity, even though in quantities below the cut-off value, are also shown; shown are mercury and lead due to electricity generation. Raw materials and emissions for a cradle-to-product gate inventory are generally far greater than those resources and emissions that occur at the production site; the exception to this comparison are VOCs and formaldehyde; on-site contributes 100% of the VOC emissions because the databases used for fuels, chemicals, and electricity only report individual VOC emissions and not their total grouping. Whereas, on-site emissions of formaldehyde are 67% since it is produced in the on-site production of the formaldehyde and the resin. The difference between on-site and cradle-to-product gate resource use can be found by comparing Tables 3.3 and 3.6, and emissions differences by comparing Tables 3.5 and 3.7.

Table 3.6. LCI output of allocated, cumulative raw material use cradle-to-product gate for the production of 1.0 kg of MUF resin at 60% solids.

Raw material	kg/kg
Aluminium, 24% in bauxite, 11% in crude ore, in ground	4.62E-05
Barite, 15% in crude ore, in ground	1.27E-06
Calcite, in ground	1.04E-03
Carbon dioxide, in air	2.89E-05
Clay, unspecified, in ground	2.18E-04
Coal, 26.4 MJ per kg, in ground	8.00E-02
Coal, brown, in ground	1.97E-04
Coal, hard, unspecified, in ground	1.60E-04
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.02E-06
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	5.67E-06
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.51E-06
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	7.46E-06
Fluorspar, 92%, in ground	1.72E-06
Gas, mine, off-gas, process, coal mining/m3	1.21E-06
Gas, natural, 46.8 MJ per kg, in ground	4.07E-01
Gas, natural, in ground	8.23E-05
Gravel, in ground	8.34E-03
Iron, 46% in ore, 25% in crude ore, in ground	8.21E-06
Limestone, in ground	4.61E-03
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	2.94E-06
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	5.94E-06
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.84E-04
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.27E-06
Oil, crude, 42 MJ per kg, in ground	1.57E-01
Oil, crude, in ground	3.25E-04
Sodium chloride, in ground	4.53E-04
Uranium, 2291 GJ per kg, in ground	3.41E-07
Uranium, in ground	8.89E-09
Water, cooling, unspecified natural origin/m3	4.66E+00
Water, lake	1.00E-04
Water, process, drinking	2.87E-01
Water, process, unspecified natural origin/kg	6.88E-01
Water, process, well, in ground	1.03E-01
Water, river	1.35E-02
Water, salt, ocean	6.97E-04
Water, salt, sole	2.37E-04
Water, unspecified natural origin/m3	1.19E+00
Water, well, in ground	3.73E-02
Wood and wood waste, 9.5 MJ per kg	3.10E-04
Wood, hard, standing	2.16E-06
Wood, soft, standing	1.21E-05
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	1.09E-05
	MJ/kg
Electricity from other gases	4.22E-03
Electricity from other renewables	2.43E-02
Energy, from hydro power	7.18E-02
Energy, gross calorific value, in biomass	2.97E-04
Energy, kinetic (in wind), converted	8.00E-05
Energy, potential (in hydropower reservoir), converted	8.46E-03
Energy, solar, converted	1.18E-06

Table 3.7. LCI output of allocated, cumulative emissions cradle-to-product gate for the production of 1.0 kg of MUF resin at 60% solids.

Emissions to air	**kg/kg**
Acetic acid	5.25E-06
Aldehydes, unspecified	2.36E-05
Aluminum	4.89E-06
Ammonia	1.91E-03
Benzene	5.89E-06
Butane	1.03E-05
Carbon dioxide, biogenic	4.88E-04
Carbon dioxide, fossil	1.68E+00
Carbon disulfide	2.05E-06
Carbon monoxide	2.27E-03
Carbon monoxide, fossil	1.52E-03
Dimethyl ether	2.26E-05
Dinitrogen monoxide	1.14E-05
Ethanol	1.52E-06
Formaldehyde	1.17E-05
Hydrocarbons, aliphatic, alkanes, unspecified	3.06E-06
Hydrogen chloride	2.18E-05
Hydrogen fluoride	2.74E-06
Isocyanic acid	3.49E-04
Lead	3.23E-07
Mercury	7.80E-09
Methane	3.03E-03
Methane, biogenic	2.61E-06
Methane, fossil	7.07E-04
Methanol	1.69E-04
Methyl formate	1.34E-06
Nickel	3.51E-06
Nitrogen oxides	3.84E-03
NMVOC, non-methane volatile organic compounds, unspecified origin	4.81E-03
Organic substances, unspecified	1.28E-04
Particulates	1.65E-06
Particulates, < 10 um	1.82E-04
Particulates, < 2.5 um	5.97E-04
Particulates, > 10 um	4.64E-04
Particulates, > 2.5 um, and < 10um	2.35E-04
Particulates, unspecified	2.45E-04
Pentane	1.76E-05
Propane	3.11E-06
Sodium	3.81E-06
Sulfur dioxide	3.23E-04
Sulfur oxides	1.54E-02
Toluene	3.09E-06
Vanadium	1.32E-05
VOC, volatile organic compounds	4.94E-05
Water	7.00E-06
	MJ/kg
Heat, waste	2.39E+01
	Bq/kg
Noble gases, radioactive, unspecified	1.49E+02
Radioactive species, unspecified	3.81E+03
Radon-222	2.86E+02

Emissions to water	**kg/kg**
Aluminum	3.67E-06
Ammonia, as N	1.30E-04
Ammonium, ion	1.86E-04
BOD5, Biological Oxygen Demand	7.51E-04
Boron	8.14E-06
Calcium, ion	3.42E-05
Chloride	1.06E-03
COD, Chemical Oxygen Demand	4.03E-04
DOC, Dissolved Organic Carbon	8.88E-05
Formaldehyde	1.09E-04
Iron	1.10E-05
Iron, ion	5.25E-06
Lead	6.48E-08
Manganese	6.29E-06
Mercury	2.77E-10
Metallic ions, unspecified	3.69E-06
Methanol	9.12E-06
Nickel, ion	1.52E-06
Nitrogen	6.27E-05
Nitrogen, organic bound	1.01E-06
Oils, unspecified	3.86E-04
Organic substances, unspecified	6.31E-05
Phenol	3.06E-06
Phosphate	1.12E-06
Phosphorus	3.04E-06
Silicon	3.68E-04
Sodium, ion	2.90E-05
Solids, inorganic	2.40E-04
Solved solids	2.16E-02
Sulfate	9.05E-04
Sulfuric acid	2.03E-06
Suspended solids, inorganic	3.94E-04
Suspended solids, unspecified	3.35E-04
TOC, Total Organic Carbon	8.88E-05
	MJ/kg
Heat, waste	1.24E-01
	Bq/kg
Hydrogen-3, Tritium	6.66E+00

Emissions to land	**kg/kg**
Oils, unspecified	1.32E-06
Solids	5.09E-05
Waste, solid	7.51E-02

3.6 Cradle-to-Product Gate Resource Use for Embodied Energy

The embodied energy to produce MUF resin can be given in several formats. For this study it is useful to examine the energy breakdown in terms of both its source of fuel and feedstock in the ground and its contribution by the various input substances. The natural gas and crude oil feedstock to produce chemicals were considered in terms of their higher heating values along with the energy of the various fuels.

Table 3.8 gives the cumulative energy equivalent from cradle-to-product gate for the production of MUF resin in terms of its fuel and feedstock source in the ground. To produce 1.0 kg of resin it takes a total of 31.66 MJ of embodied energy based on the higher heating values of the various fuels and feedstock. Natural gas provides 69.9% of the energy, followed by crude oil at 22.7% and coal at 6.7%, and all other sources are of minor significance. As expected the natural gas use is high since it is not only used as fuel for processing and electricity, it is the source feedstock for the primary input chemicals.

Table 3.8. Cradle-to-gate fuel and electricity use in terms of their energy equivalence for the manufacture of 1.0 kg of MUF resin at 60% non-volatile solids.

Energy use by fuel source	Energy[1] MJ/kg resin	Contribution %
Coal in ground	2.11E+00	6.7
Crude oil in ground	7.18E+00	22.7
Natural gas in ground	2.21E+01	69.9
Uranium in ground	1.33E-01	0.4
Wood fuel	3.23E-03	0.0
Electricity from other gases	4.22E-03	0.0
Electricity from other renewables	2.43E-02	0.1
Energy, from hydro power	7.18E-02	0.2
Energy, potential (hydropower reservoir)	8.46E-03	0.0
Total	31.66	100.0

[1] Electricity at 3.6 MJ/kWh, uranium at 381,000 MJ/kg and other fuels at their higher heating value (HHV) of coal 26.2 MJ/kg, crude oil 45.5 MJ/kg, natural gas 54.4 MJ/kg, and wood 20.9 MJ/kg.

Energy equivalence by the input chemicals and process component to manufacturing can be of value in assessing the major contributors and for identifying opportunities for reducing energy use. Table 3.9 gives the embodied energy breakdown for manufacturing MUF resin from in-ground resource to the output gate of the resin plant. The total energy is 31.66 MJ/kg resin with the urea and the methanol providing the major contributions of 46.1% and 34.1% respectively, and a lesser contribution of 14.9% by melamine, and all other contributors are relatively insignificance. Transportation of chemical inputs to the plant represents only 1.3% of the total energy. Energy to provide resin manufacturing process energy and electricity for heat and emissions control represents only 3.4% of the total.

Table 3.9. A breakdown of energy contributors to produce 1.0 kg of MUF resin at 60% solids cradle-to-product gate (based on HHV of fuel).

Energy use by process component	Energy MJ/kg resin	Contribution %
Melamine	4.72E+00	14.9
Urea	1.46E+01	46.1
Methanol	1.08E+01	34.1
Formic acid 10% solids	3.95E-02	0.1
Ammonium sulfate 20% solids	1.16E-03	0.0
Sodium hydroxide 50% solids	7.82E-03	0.0
Trailer diesel	2.01E-01	0.6
Diesel locomotive	2.21E-01	0.7
Natural gas	6.92E-01	2.2
Natural gas equipment (surrogate propane)	7.95E-07	0.0
Electricity, USA average process	2.28E-01	0.7
Electricity, USA average emissions equipment	1.55E-01	0.5
TOTAL	31.66	100

3.7 Sensitivity Analysis

The sensitivity analysis involves examining the impact of varying an input parameter such as fuel to a process and examining the magnitude of the change of an output parameter such as resource use or carbon dioxide (fossil) emission. The magnitude of the impact is dependent on the input parameter and also on the output parameter of interest. Tables 3.10 and 3.11 show the dominant contributors to substance use are input materials of melamine, urea and methanol with little if any contributions from on-site inputs of chemicals, fuel, and electricity, and little if any contribution by transportation of chemicals to the resin plant. Although the formic acid may seem like a major contributor to some substances, its contributions are for lesser substances in terms of mass use so the impacts are much smaller.

Changing any of the three dominant input parameters will have a significant impact on most resource uses and emissions whereas changes of other lesser input parameters such as transportation fuels, plant input chemicals of formic acid, ammonium sulfate, sodium hydroxide, and on-site use of natural gas and electricity will have little if any impact. An analysis of the sensitivity for UF resin which is very similar to the MUF contributors, showed that varying the input of urea to the process by +10%, resulted in proportional changes to the percentage of contribution of each raw material and emission ranging from 0 to an expected 10% for those substances that urea is the sole contributor. Like changes of the other major contributors of melamine and methanol would result in proportional changes in the use of various substances. Therefore, a sensitivity analysis of MUF resin isn't needed since the results would be similar.

Table 3.10. Contribution by input parameter to use of raw materials for the manufacture of MUF resin.

Substance			Process input chemicals						Transportation		MUF process	
		MUF resin process	Melamine	Urea	Methanol	Formic acid	Ammonium sulfate	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
	kg/kg resin	% contribution										
Aluminium, 24% in bauxite, 11% in crude ore, in ground	4.62E-05	0	1	3	96	0	0	0	0	0	0	0
Barite, 15% in crude ore, in ground	1.27E-06	0	0	1	25	0	0	74	0	0	0	0
Calcite, in ground	1.04E-03	0	21	73	5	0	0	1	0	0	0	0
Carbon dioxide, in air	2.89E-05	0	9	33	20	36	0	2	0	0	0	0
Clay, unspecified, in ground	2.18E-04	0	21	73	6	0	0	0	0	0	0	0
Coal, 26.4 MJ per kg, in ground	8.00E-02	0	24	55	9	0	0	0	0	0	0	7
Coal, brown, in ground	1.97E-04	0	1	4	21	71	0	2	0	0	0	0
Coal, hard, unspecified, in ground	1.60E-04	0	5	17	27	48	0	3	0	0	0	0
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.02E-06	0	0	0	100	0	0	0	0	0	0	0
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	5.67E-06	0	0	0	100	0	0	0	0	0	0	0
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.51E-06	0	0	0	100	0	0	0	0	0	0	0
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	7.46E-06	0	0	0	100	0	0	0	0	0	0	0
Fluorspar, 92%, in ground	1.72E-06	0	19	66	15	1	0	0	0	0	0	0
Gas, mine, off-gas, process, coal mining/m3	1.21E-06	0	6	23	25	44	0	2	0	0	0	0
Gas, natural, 46.8 MJ per kg, in ground	4.07E-01	0	12	37	47	0	0	0	0	0	0	0
Gas, natural, in ground	8.23E-05	0	8	28	24	38	0	1	0	0	0	0
Gravel, in ground	8.34E-03	0	21	75	4	0	0	0	0	0	0	0
Iron, 46% in ore, 25% in crude ore, in ground	8.21E-06	0	1	3	96	0	0	0	0	0	0	0
Limestone, in ground	4.61E-03	0	24	55	9	0	0	0	0	0	0	7
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	2.94E-06	0	0	0	100	0	0	0	0	0	0	0
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	5.94E-06	0	0	0	100	0	0	0	0	0	0	0
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.84E-04	0	21	76	3	0	0	0	0	0	0	0
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.27E-06	0	0	2	98	0	0	0	0	0	0	0
Oil, crude, 42 MJ per kg, in ground	1.57E-01	0	21	71	2	0	0	0	3	3	0	0
Oil, crude, in ground	3.25E-04	0	4	13	12	71	0	0	0	0	0	0
Sodium chloride, in ground	4.53E-04	0	0	1	20	0	0	79	0	0	0	0
Uranium, 2291 GJ per kg, in ground	3.41E-07	0	24	55	9	0	0	0	0	0	0	7
Uranium, in ground	8.89E-09	0	3	12	20	62	0	2	0	0	0	0
Water, cooling, unspecified natural origin/m3	4.66E+00	0	42	0	53	4	0	0	0	0	0	0
Water, lake	1.00E-04	0	18	63	13	5	0	0	0	0	0	0
Water, process, drinking	2.87E-01	0	0	0	100	0	0	0	0	0	0	0
Water, process, unspecified natural origin/kg	6.88E-01	100	0	0	0	0	0	0	0	0	0	0
Water, process, well, in ground	1.03E-01	100	0	0	0	0	0	0	0	0	0	0
Water, river	1.35E-02	0	11	39	30	19	0	1	0	0	0	0
Water, salt, ocean	6.97E-04	0	3	10	20	65	0	2	0	0	0	0
Water, salt, sole	2.37E-04	0	2	8	11	77	0	0	0	0	0	0
Water, unspecified natural origin/m3	1.19E+00	0	54	46	0	0	0	0	0	0	0	0
Water, well, in ground	3.73E-02	0	21	74	4	2	0	0	0	0	0	0
Wood and wood waste, 9.5 MJ per kg	3.10E-04	0	17	52	26	0	0	0	1	1	0	1
Wood, hard, standing	2.16E-06	0	4	13	24	58	0	2	0	0	0	0
Wood, soft, standing	1.21E-05	0	12	41	19	27	0	1	0	0	0	0
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	1.09E-05	0	0	0	100	0	0	0	0	0	0	0
	MJ/kg											
Electricity from other gases	4.22E-03	0	25	55	8	0	0	0	0	0	0	7
Electricity from other renewables	2.43E-02	0	25	55	8	0	0	0	0	0	0	7
Energy, from hydro power	7.18E-02	0	25	55	8	0	0	0	0	0	0	7
Energy, gross calorific value, in biomass	2.97E-04	0	10	36	20	32	0	1	0	0	0	0
Energy, kinetic (in wind), converted	8.00E-05	0	1	4	20	72	0	2	0	0	0	0
Energy, potential (in hydropower reservoir), converted	8.46E-03	0	20	69	7	4	0	0	0	0	0	0
Energy, solar, converted	1.18E-06	0	2	6	20	70	0	2	0	0	0	0

Table 3.11. Contribution by input parameter to air emissions for the manufacture of MUF resin.

Emissions to air		Process input chemicals							Transportation		UF process	
		MUF resin	Melamine	Urea	Methanol	Formic acid	Ammonium sulfate	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
	kg/kg resin	% contribution										
Acetic acid	5.25E-06	0	22	78	0	0	0	0	0	0	0	0
Aldehydes, unspecified	2.36E-05	0	18	48	5	0	0	0	13	15	0	0
Aluminum	4.89E-06	0	20	69	11	0	0	0	0	0	0	0
Ammonia	1.91E-03	0	28	72	0	0	0	0	0	0	0	0
Benzene	5.89E-06	0	22	78	0	0	0	0	0	0	0	0
Butane	1.03E-05	0	22	78	0	0	0	0	0	0	0	0
Carbon dioxide, biogenic	4.88E-04	0	15	45	33	2	0	0	1	1	0	1
Carbon dioxide, fossil	1.68E+00	0	20	64	11	0	0	0	1	1	0	1
Carbon disulfide	2.05E-06	0	19	67	14	0	0	0	0	0	0	0
Carbon monoxide	2.27E-03	0	13	38	36	0	0	0	5	3	0	0
Carbon monoxide, fossil	1.52E-03	0	22	78	0	0	0	0	0	0	0	0
Dimethyl ether	2.26E-05	100	0	0	0	0	0	0	0	0	0	0
Dinitrogen monoxide	1.14E-05	0	22	74	2	0	0	0	0	0	0	1
Ethanol	1.52E-06	0	22	78	0	0	0	0	0	0	0	0
Formaldehyde	1.17E-05	66	7	26	0	0	0	0	0	0	0	0
Hydrocarbons, aliphatic, alkanes, unspecified	3.06E-06	0	22	78	0	0	0	0	0	0	0	0
Hydrogen chloride	2.18E-05	0	23	63	6	0	0	0	0	0	0	4
Hydrogen fluoride	2.74E-06	0	24	61	7	0	0	0	0	0	0	5
Isocyanic acid	3.49E-04	0	100	0	0	0	0	0	0	0	0	0
Lead	3.23E-07	0	21	74	4	0	0	0	0	0	0	0
Mercury	7.80E-09	0	23	58	10	0	0	0	0	0	0	5
Methane	3.03E-03	0	13	39	43	0	0	0	0	0	0	1
Methane, biogenic	2.61E-06	0	22	77	0	0	0	0	0	0	0	0
Methane, fossil	7.07E-04	0	13	45	42	0	0	0	0	0	0	0
Methanol	1.69E-04	3	0	1	95	0	0	0	0	0	0	0
Methyl formate	1.34E-06	0	0	0	0	100	0	0	0	0	0	0
Nickel	3.51E-06	0	22	77	1	0	0	0	0	0	0	0
Nitrogen oxides	3.84E-03	0	18	49	21	0	0	0	3	4	0	1
NMVOC, non-methane volatile organic compoun	4.81E-03	0	14	44	37	0	0	0	1	2	0	0
Organic substances, unspecified	1.28E-04	0	16	30	2	0	0	0	48	3	0	0
Particulates	1.65E-06	100	0	0	0	0	0	0	0	0	0	0
Particulates, < 10 um	1.82E-04	0	19	38	7	0	0	0	9	24	0	1
Particulates, < 2.5 um	5.97E-04	0	22	78	0	0	0	0	0	0	0	0
Particulates, > 10 um	4.64E-04	0	22	78	0	0	0	0	0	0	0	0
Particulates, > 2.5 um, and < 10um	2.35E-04	0	22	78	0	0	0	0	0	0	0	0
Particulates, unspecified	2.45E-04	0	23	55	11	0	0	0	0	0	0	5
Pentane	1.76E-05	0	22	78	0	0	0	0	0	0	0	0
Propane	3.11E-06	0	22	77	0	1	0	0	0	0	0	0
Sodium	3.81E-06	0	22	78	0	0	0	0	0	0	0	0
Sulfur dioxide	3.23E-04	0	21	74	5	1	0	0	0	0	0	0
Sulfur oxides	1.54E-02	0	13	39	44	0	0	0	0	0	0	1
Toluene	3.09E-06	0	22	78	0	0	0	0	0	0	0	0
Vanadium	1.32E-05	0	22	78	0	0	0	0	0	0	0	0
VOC, volatile organic compounds	4.94E-05	100	0	0	0	0	0	0	0	0	0	0
Water	7.00E-06	0	19	68	12	0	0	0	0	0	0	0
	MJ/kg resin											
Heat, waste	2.39E+01	0	21	73	6	0	0	0	0	0	0	0
	Bq/kg resin											
Noble gases, radioactive, unspecified	1.49E+02	0	3	10	20	65	0	2	0	0	0	0
Radioactive species, unspecified	3.81E+03	0	24	55	10	0	0	0	0	0	0	7
Radon-222	2.86E+02	0	3	12	20	63	0	2	0	0	0	0

3.8 Carbon Content and Footprint of MUF Resin

When it comes to climate change and related issues as a result of increased greenhouse gas emissions to the atmosphere, two topics are of interest: 1) the amount of carbon store in a material that that can in some instances be considered as an offset when sequestered near-term to reduce the amount of CO_2 emissions to the atmosphere, and 2) the carbon footprint of a material giving the amount of greenhouse gases released to the atmosphere during its life cycle. The sum of the two values with carbon store as a negative value gives the net CO_2 impact of a material upon the environment

Cured MUF resin is comprised of 27% of carbon by weight for 0.270 kg/kg cured resin. The percentage is based on in-mill additives and no loss of formaldehyde. The carbon content is an estimate which can vary with changes in formulation and resin mix. Unfortunately this carbon cannot be considered as a carbon store offset to CO_2 emissions since it is not continuously renewing in the carbon cycle. The resin carbon was sequestered hundreds of million years ago during the formation of the fossil fuels that are used as its feedstock. The carbon in the resin is unlike the carbon stored in trees and wood which was sequestered near-term within the last 30-100 years, is part of a continuously renewing carbon cycle, and can be counted as an offset against emissions of CO_2 to the atmosphere when looking at a material's carbon footprint and impact upon global warming.

The carbon footprint is determined by the CO_2 equivalent of all greenhouse gas (GHG) emissions during the life cycle of a product, in this case from resources in the ground through extraction, deliveries and manufacturing of the liquid MUF resin. The CO_2 equivalent of each GHG can be determined by multiplying its comparative reactive factor in the atmosphere to that for carbon dioxide based on a 100-year time horizon (IPCC 2007). There are three GHGs that normally occur for the life cycle of wood products—CO_2 (fossil fuel contributions), CH_4 (methane), and N_2O (listed as nitrous oxide and dinitrogen oxide in the LCI output). The total carbon footprint for the life cycle of MUF resin from cradle-to-gate is given by the following—the values of each contribution are given in Table 3.6:

$$\text{Carbon Footprint kg-}CO_2\text{ eq} = CO_2\text{ kg} + (CH_4\text{ kg x 25}) + (N_2O\text{ kg x 298})$$

The carbon footprint in kg-CO_2 equivalent (eq) is determined by the mass of each contributor times how reactive it is in comparison to CO_2 in the atmosphere, e.g., CH_4 is 23 times more reactive than CO_2 and N_2O is 296 times more reactive than CO_2. Considering the total emissions from cradle-to-product gate for each contributor gives a total of 2.9581 kg-CO_2 eq. per kg of 100% solids MUF resin, see Table 3.12. These emissions are generated in the process of extracting the fuel, generation of electricity, delivery of fuel, and the combustion fuel in the manufacture of the resin.

Table 3.12. The carbon footprint given in kg-CO2 equivalent (eq) for 100% solids MUF resin.

Greenhouse gas (GHG)	GHG Contribution kg/kg resin 60% solids	CO_2 equiv. multiplier	Carbon Footprint kg-CO_2 eq/kg resin 100% solids
CO_2	1.677934	1	2.7966
Methane (CH_4)	0.00374	25	0.1558
Nitrous oxide (N_2O)	0.0000114	298	0.0057
Total			2.9581

3.9 Study Discussion

The data documented in this chapter on the manufacture of MUF resin forms a foundation for the scientific assessment of its environmental performance. The MUF resin data should not be considered as a stand alone product; rather it should be used when conducting life-cycle inventories and assessments of wood composite products that use this resin as a bonding agent during their manufacture. Resins are an integral component and contributor to the performance of wood composites. A life-cycle assessment of the use of resins in composites can be used in a number of ways to show their favorable performance for such environmental issues as sustainability, global warming, climate change, carbon footprint, carbon storage, carbon trading and caps, carbon taxes, green purchasing, and green building. The data can be used as stated or in a life-cycle assessment to compare wood composite products to various competitive materials or assemblies of various materials. Individual LCI data of MUF resin can be used as a benchmark for process or product improvements or for comparing performance to those of other materials.

3.10 Conclusion

A cradle-to-product gate life-cycle inventory (LCI) study was conducted of manufacturing 1.0 kg of melamine-urea-formaldehyde (MUF) resin at 60% solids—the LCI functional unit for this study—in the U.S. The study covered data analyses from the raw resources in the ground through resin manufacturing for the production year 2005. Production data was collected by survey of resin manufacturers representing 77% of total U.S. production of MUF resin for the particleboard, MDF, and hardwood plywood industries that annually used 86,588,000 kg of MUF resin at 60% solids. Secondary LCI data from the Franklin Associates Limited (FAL) and Ecoinvent databases were used for input chemicals, fuels, electricity and transportation; Ecoinvent data was adjusted to U.S. fuels, electricity, and transportation values where appropriate using FAL processes.

The quality of the LCI data collected for the manufacture of MUF resin was high as judged by assessments for similarity of values, molar ratio of formaldehyde to urea plus melamine, and the mass flow of material in and out of the process. Any data questions were resolved by re-contacting the manufacturers that participated in the survey. The molar ratio formaldehyde to urea plus melamine was found to be 1.16 within the expected range of 1.15 to 1.30.

Assigning of environmental burden in the production of MUF resin was entirely to the product since no co-products are produced during the process. Of the output functional unit of 1.0 kg of MUF resin at 60% solids, the main input components were melamine of 0.081 kg, urea at 0.397 kg and methanol at 0.304 kg; water at 0.79 kg for resin and processing use; and a number of lesser significant quantities of acids and caustics were used. The methanol is used in reactors to produce formaldehyde which is then used with the addition of melamine and urea in another reactor to produce the MUF resin.

Environmental impacts were assessed for those at the resin manufacturing site (referred to as on-site emissions) and those for cradle-to-product gate which begins with resources in the ground through extraction, generation, delivery, and resin manufacture. On-site impacts are small compared to the cradle-to-product gate impacts. Per 1.0 kg of liquid resin the on-site energy use of 0.643 MJ compared to 31.66 MJ/kg resin for cradle-to-product gate, and emissions to air such as CO_2, CO, VOCs, particulate, formaldehyde and methanol are 2%, 0.3%, 100% (cradle-to-gate chemicals only consider individual VOC contribution and not as a grouping), 0.7%, 67% and 3% of the cradle-to-product gate values. The on-site emissions to water are also smaller. Even water use was much less at only 9% of cradle-to-gate values. Overall the resin operations are resource efficient and relatively friendly to the environment.

In terms of energy equivalent for fuels and feedstock from cradle-to-product gate, the manufacture of melamine, urea and methanol from in-ground fuel resources contributed to 14.9%, 46.1% and 34.1% of the total energy, respectively. The transportation of chemical inputs to the resin plants, and on-site processing fuels and electricity were all minor contributors to the total energy.

A sensitivity of the input parameters to the output use of materials and emissions to air, water, and land were likewise dominated by input melamine, urea and methanol chemicals. Other inputs of on-site fuel and electricity use, and transportation of chemicals to the plant, all were minor contributors. Based on the earlier analysis of UF resin, changing melamine, urea and/or methanol would result in expected proportional outputs of emissions; changes in other minor parameters would generally result in no significant changes in output.

The carbon footprint from cradle-to-gate to produce MUF resin is 2.958 kg-CO_2 eq per 1.0 kg of 100% solids resin. The carbon footprint accounts for all greenhouse gas emissions during the life cycle of a product, in this case from cradle-to-gate. Although MUF cured resin has a carbon component of 27%, it is not considered as an offset for CO_2 emissions to the atmosphere during processing since its carbon was not sequestered near-term and it is not a continuously renewable carbon cycle.

To benefit from the availability of the LCI database for MUF resin, the following additional studies are recommended: 1) extract pertinent data that documents the favorable environmental performance of MUF resin and 2) edit any prior CORRIM LCI studies that used MUF resin to include the LCI data developed in this study.

4.0 Life-Cycle Inventory of Phenol-Formaldehyde Resin

4.1 Introduction

4.1.1 Survey Data

The phenol-formaldehyde (PF) resin survey data was for 13 plants in U.S. that represented 62% of total production for the year 2005. Total annual production was 1,717,500,000 lbs (779,063,000 kg) of neat resin at 47.4% non-volatile solids content. The resin is used for the production of plywood, laminated veneer lumber (LVL), and oriented strand board (OSB) and is based on its use as documented in earlier CORRIM studies (Wilson and Sakimoto 2005, Wilson and Dancer 2005a, and Kline 2005). The PF resin for OSB is similar to that used for plywood and LVL with the primary difference being that a small quantity of urea is added to make the OSB PF resin. A small quantity of PF resin is used for production of hardboard.

4.1.2 Materials Flow

Those materials considered in the LCI analysis of PF resin production included those listed in Table 4.1. The process is similar to the production of UF resin except that phenol instead of urea is reacted with formaldehyde. Input materials considered were phenol, methanol, sodium hydroxide, and water, plus a number of other caustic and acid chemicals of lesser significance. The silver or molybdenum/iron metal oxide catalyst used to produce formaldehyde from methanol was not included in the analysis because it too is a small contributor to the analysis and the manufacturers considered this information proprietary.

Table 4.1. Listing of input chemicals used to produce phenol-formaldehyde (PF) resin.

Input Material	Product
Phenol (100%)[1]	Phenol-formaldehyde resin (47.4%)[2]
Methanol (100%)	
Sodium hydroxide (50%)	
Water	

[1] Solids content or solution strength of chemicals into the plant.

[2] Solids content of resin out of the plant.

4.1.3 Transportation

The delivery of chemicals to the resin plants is by both truck and rail. Table 4.2 gives the one-way deliver distances. Usually the truck deliveries have no back haul of other materials. The t•km (the mass (t for tonne) times distance traveled (km)) values are used in the SimaPro software by accessing the FAL database to obtain U.S. typical environmental impacts for truck and rail transportation. Other chemicals are used in the resin production process but their quantity and contribution to environmental impacts were so insignificant that they were not included in either the input data or the transportation calculations.

Table 4.2. One-way delivery distance for input chemicals to PF resin plants.

Chemical	Transportation mode	% mode	One-way distance km	Chemical weight kg	t	Truck tkm	Rail tkm
Phenol	truck	36	230	0.244	2.44E-04	2.02E-02	
Phenol	rail	64	1,615	0.244	2.44E-04		2.52E-01
Methanol	rail	100	2,025	0.209	2.09E-04		4.23E-01
Sodium hydroxide	truck	100	297	0.122	1.22E-04	3.62E-02	
Total						5.64E-02	6.75E-01

4.2 Product Yields

The inputs to produce 1.0 kg of neat phenol-formaldehyde (PF) resin at 47.4% non-volatile solids content consist of the two primary chemicals of phenol at 0.244 kg and methanol at 0.209 kg, a lesser amount of sodium hydroxide of 0.061, and 0.349 kg of water. A significant portion of the processing water is recycled back into the resin. See Table 4.3 for all inputs and outputs, except emissions, for the manufacture of PF resin. Electricity is used for processing such as fans and pumps, and for operating emissions control equipment, while the natural gas is used for boiler fuel and emission control equipment, and propane is used for fuel in forklifts.

Table 4.3. Inputs for the production of 1.0 kg of PF resin at 47.4% solids.

	SI Unit	Unit/kg PF 47.4% solids
INPUTS		
Chemicals[1]		
Phenol	kg	2.44E-01
Methanol	kg	2.09E-01
Sodium hydroxide (50%)	kg	6.10E-02
Water[2]		
Water for producing PF resin	kg	2.97E-01
Water use; cooling tower	kg	1.56E-02
Water, well source	kg	3.72E-02
Electricity and fuel use		
Electricity	kWh	2.20E-02
Electricity for emissions control	kWh	1.36E-02
Natural gas	m^3	8.21E-03
Propane	L	2.93E-06
OUTPUTS[3]		
PF liquid resin (47.4% solids)	kg	1.0

[1] All chemical weights given at either 100% non-volatile solids or dry except for PF resin given on a 47.4% solids basis.

[2] There is a significant amount of water recycling back into the resin.

[3] Emissions to air, water and land listed in separate table.

The molar ratio of formaldehyde to phenol was used as a check on the quality of the data. Assuming that it takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde, the molar ratio of formaldehyde to phenol for this representative resin system was determined to be 2.23 which is close to the typical of 2.25 and within the expected range of values of 2.00 to 2.50 for a contemporary, commercial PF resin for use in the softwood plywood and laminated veneer lumber industries. The value of the molar ratio affects both the performance of the resin and the properties of the composite panel made with this resin.

4.3 Manufacturing Energy Summary

4.3.1 Sources of Energy and Electricity

Energy for the production of PF resin comes from electricity to operate fans and pumps, natural gas to generate steam (boiler) for heating reactors and input chemicals, and propane gas (LPG) to operate forklift equipment. Electricity and natural gas are also used to operate regenerative thermal oxidizers (RTOs) at some plants to control air emissions. A breakdown by fuel source for the production of electricity for the U.S. in 2005 was given previously in Table 1.1.

Natural gas is the primary fuel in resin manufacturing; it is used for generating steam that is used to heat input chemicals and reactors; and is used for combusting VOCs and HAPs in RTO emission control systems. The natural gas and/or electricity use would have been greater had all resin plants used RTO emissions control devices. In addition to natural gas use, a small amount of propane fuel was used to operate fork lift trucks and handlers within the plant. Table 4.4 gives the energy use on-site for manufacturing PF resin. The natural gas provides 71% of the energy and the electricity provides 29%. The propane is an insignificant contributor to the energy use.

Table 4.4. On-site fuel and electricity use in terms of their energy equivalence for the manufacture of 1.0 kg of PF resin at 47.4% non-volatile solids.

Energy use[1]	Unit	Unit/kg PF resin	MJ/kg PF resin	% Use
Electricity process	MJ	7.94E-02	7.94E-02	17.9
Electricity emissions control	MJ	4.91E-02	4.91E-02	11.1
Natural gas	m^3	8.21E-03	3.15E-01	71.0
Propane	L	2.93E-06	1.12E-07	0.0
Total energy			4.43E-01	100.0

[1] Electricity at 3.6 MJ/kWh and fuels at their higher heating value (HHV) of natural gas at 54.4 MJ/kg and propane at 54.0 MJ/kg.

4.4 Plant Emissions for Producing PF Resin

Outputs for the production of 1.0 kg of PF resin at 47.4% solids include emissions to air, water and land, see Table 4.5. Emissions are generated due to emissions from the combustion of gases and the chemical reactions in the reactors. For combustion, only CO_2 and CO are given—both were calculated using the SimaPro software, actual gas use, and the FAL database for U.S. fuels—the total emissions are determined by considering natural gas and propane on-site fuel use. All other emissions were collected by survey; they include emissions to air of particulate, volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) of formaldehyde and methanol that come off of the absorber and the reactor. The dimethyl ether emissions occur for the molybdenum/iron oxide process and not at any significant amount for the silver oxide process in the production of formaldehyde. Emissions to water were not provided by the manufacturers since all excess water is recycled back into the resin manufacture.

Table 4.5. On-site reported outputs for the production of 1.0 kg of PF resin at 47.4% non-volatile solids.

	Survey Wt. Average kg/kg PF 47.4% solids
Production output	
Phenol-formaldehyde resin (47.4% solids)	1.00
Emissions to air[1]	
CO_2[2], fossil (GHG)[3]	1.76E-02
CO[2]	3.81E-05
VOC	2.89E-05
Particulate	2.31E-06
Formaldehyde (HAP)[3]	6.69E-06
Methanol (HAP)[3]	3.20E-06
Phenol (HAP)[3]	2.04E-06
Dimethyl ether	4.73E-06
Emissions to land[1]	
Solids	2.00E-04

[1] Emissions data reported in survey.

[2] CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant.

[3] HAP hazardous air pollutant; GHG greenhouse gas.

4.5 Cradle-to-Product Gate Process Related Resource Use and Emissions

The life-cycle inventory for the production of PF resin covers its cycle from in-ground resources through the production and delivery of input chemicals and fuels, through its manufacture of a resin as shipped to the customer. It examines the use of all resources, fuels and electricity and all emissions to air, water and land; it also includes feedstock of natural gas and crude oil used to produce the chemicals. Table 4.6 gives the raw materials and energy sources, and Table 4.7 gives emissions to air, water and land for the cradle-to-gate inventory. The raw materials in the ground include coal, natural gas, limestone, crude oil, and uranium, water usage and others. Materials of quantities smaller than 1.0E-06 kg/kg are not included in the listing. Because life-cycle studies involve tracing resource use back to its in-ground resources, some materials or substances can involve many steps of backtracking to their source, resulting in the use of a large numbers of substances, many of insignificant quantity. For this study a filter was used to remove insignificant substances from the listing. The filter varied depending on whether the emission was to air, water, or land. The exception was for substances that are highly toxic such as uranium, mercury, and lead where values less than the cut-off value are shown.

Some sources of energy or fuels cannot be traced back to their original resource in the ground. Such energies include “energy from hydro power,” “electricity from other gases” and “electricity from renewables” which are not defined in terms of identifiable fuels are listed in a separate category defined as Energy and are given in MJ/kg of resin.

Emissions for the cradle-to-gate scenario are listed in Table 4.7. The emissions to air and water used a cut-off value of 1.0E-06 kg/kg resin, and radiation type emissions had a cut-off of 1.0E+00 Bq/kg resin.

Emissions to land used a cut-off of 1.0E-06 kg/kg resin. Some emissions because of their toxicity, even though in quantities below the cut-off value, are also shown, e.g., mercury and lead due to electricity generation. Raw materials and emissions for a cradle-to-product gate inventory are generally far greater than those resources and emissions that occur at the production site; the exception to this comparison are VOCs and formaldehyde; on-site contributes 100% of the VOC emissions because the databases used for fuels, chemicals, and electricity only report individual VOC emissions and not their total grouping. The on-site emissions of formaldehyde are 67% due to the on-site manufacture of formaldehyde and the PF resin. The difference between on-site and cradle-to-product gate resource use can be found by comparing Tables 4.3 and 4.6, and emissions differences by comparing Tables 4.5 and 4.7.

Table 4.6. LCI output of allocated, cumulative raw material use cradle-to-product gate for the production of 1.0 kg of PF resin at 47.4% solids.

Raw material	kg/kg resin
Aluminium, 24% in bauxite, 11% in crude ore, in ground	3.20E-05
Anhydrite, in ground	2.64E-06
Barite, 15% in crude ore, in ground	2.74E-04
Calcite, in ground	5.27E-03
Carbon dioxide, in air	1.64E-04
Clay, bentonite, in ground	2.78E-05
Clay, unspecified, in ground	3.92E-04
Coal, 26.4 MJ per kg, in ground	1.28E-01
Coal, brown, in ground	1.30E-03
Coal, hard, unspecified, in ground	1.94E-02
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.53E-06
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	3.90E-06
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.03E-06
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	5.13E-06
Dolomite, in ground	1.39E-06
Gas, mine, off-gas, process, coal mining/m3	9.78E-06
Gas, natural, 46.8 MJ per kg, in ground	2.28E-01
Gas, natural, in ground	1.49E-01
Gravel, in ground	2.55E-04
Iron, 46% in ore, 25% in crude ore, in ground	1.86E-04
Limestone, in ground	7.35E-03
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in grd	2.02E-06
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in grd	4.08E-06
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	5.27E-06
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.68E-06
Oil, crude, 42 MJ per kg, in ground	1.89E-02
Oil, crude, in ground	3.11E-01
Peat, in ground	6.05E-05
Sand, unspecified, in ground	3.21E-05
Shale, in ground	7.48E-06
Sodium chloride, in ground	1.04E-01
Sulfur, in ground	2.16E-05
Uranium, 2291 GJ per kg, in ground	5.46E-07
Uranium, in ground	1.20E-06
Water, cooling, unspecified natural origin/kg	1.60E-02
Water, cooling, unspecified natural origin/m3	4.37E+01
Water, lake	1.56E-04
Water, process, drinking	1.97E-01
Water, process, unspecified natural origin/kg	2.97E-01
Water, process, well, in ground	3.70E-02
Water, river	1.08E-01
Water, salt, ocean	1.54E-01
Water, salt, sole	2.41E-04
Water, unspecified natural origin/m3	4.79E-01
Water, well, in ground	7.20E-03
Wood and wood waste, 9.5 MJ per kg	1.75E-04
Wood, hard, standing	1.21E-05
Wood, soft, standing	6.88E-05
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	7.48E-06
	MJ/kg resin
Electricity from other gases	7.18E-03
Electricity from other renewables	4.13E-02
Energy, from hydro power	1.22E-01
Energy, gross calorific value, in biomass	3.98E-02
Energy, kinetic (in wind), converted	5.34E-04
Energy, potential (in hydropower reservoir), converted	3.32E-02
Energy, solar, converted	7.77E-06

Table 4.7. LCI output of allocated, cumulative emissions cradle-to-product gate for the production of 1.0 kg of PF resin at 47.4% solids.

Emissions to air	**kg/kg resin**
Aldehydes, unspecified	9.77E-06
Ammonia	4.64E-06
Benzene	4.52E-04
Carbon dioxide, biogenic	1.89E-03
Carbon dioxide, fossil	1.16E+00
Carbon monoxide	1.27E-03
Carbon monoxide, biogenic	1.65E-06
Carbon monoxide, fossil	7.36E-04
Chlorine	1.89E-06
Cumene	6.54E-04
Dimethyl ether	4.73E-06
Dinitrogen monoxide	2.86E-06
Ethene	1.82E-06
Formaldehyde	6.73E-06
Hydrocarbons, aliphatic, alkanes, cyclic	1.29E-06
Hydrocarbons, aromatic	8.38E-06
Hydrogen	4.09E-05
Hydrogen chloride	3.29E-05
Hydrogen fluoride	3.60E-06
Lead	2.87E-08
Mercury	1.21E-08
Methane	2.09E-03
Methane, biogenic	1.03E-05
Methane, fossil	4.50E-03
Methanol	1.14E-04
Nickel	1.41E-06
Nitrogen oxides	3.37E-03
NMVOC, non-methane volatile organic compounds, unspecified origin	3.05E-03
Organic substances, unspecified	6.00E-05
Particulates	2.31E-06
Particulates, < 10 um	1.52E-04
Particulates, < 2.5 um	4.16E-05
Particulates, > 10 um	5.58E-05
Particulates, > 2.5 um, and < 10um	7.00E-05
Particulates, unspecified	3.33E-04
Phenol	2.05E-06
Propene	2.42E-04
Sulfur dioxide	1.26E-03
Sulfur oxides	9.80E-03
VOC, volatile organic compounds	2.89E-05
	MJ/kg resin
Heat, waste	9.22E+00
	Bq/kg resin
Noble gases, radioactive, unspecified	9.40E+02
Radioactive species, unspecified	6.03E+03
Radon-222	1.77E+03

Emissions to water	kg/kg resin
Aluminum	6.67E-05
Ammonium, ion	5.43E-06
Antimony	1.66E-06
Benzene	1.07E-03
BOD5, Biological Oxygen Demand	1.00E-02
Boron	1.26E-05
Bromate	1.59E-05
Bromine	1.46E-06
Calcium, ion	2.96E-04
Carbonate	3.32E-05
Chlorate	1.22E-04
Chloride	1.88E-03
COD, Chemical Oxygen Demand	1.04E-02
Copper, ion	1.35E-06
Cumene	1.57E-03
DOC, Dissolved Organic Carbon	3.05E-03
Fluoride	2.80E-06
Formaldehyde	2.09E-05
Hydrocarbons, unspecified	5.72E-06
Iron	1.74E-05
Iron, ion	1.45E-05
Lead	3.47E-07
Magnesium	3.25E-05
Manganese	1.02E-05
Mercury	7.23E-09
Methanol	6.27E-06
Nitrate	3.16E-05
Nitrogen	1.24E-06
Oils, unspecified	2.23E-04
Organic substances, unspecified	3.69E-05
Phenol	2.34E-06
Phosphate	1.38E-05
Phosphorus	2.18E-06
Potassium, ion	8.47E-05
Propene	5.79E-04
Silicon	3.18E-04
Sodium, ion	1.22E-04
Solids, inorganic	1.35E-04
Solved solids	1.21E-02
Sulfate	1.39E-03
Sulfuric acid	3.07E-06
Suspended solids, unspecified	3.36E-04
TOC, Total Organic Carbon	3.06E-03
Zinc, ion	1.89E-06
	MJ/kg resin
Heat, waste	9.07E-02
	Bq/kg resin
Hydrogen-3, Tritium	4.19E+01

Emissions to land	kg/kg resin
Solids	2.00E-04
Waste, solid	7.87E-02

4.6 Cradle-to-Product Gate Resource Use for Embodied Energy

The embodied energy to produce PF resin can be given in several formats. For this study it is useful to examine the energy breakdown in terms of both its source of fuel and feedstock in the ground and its contribution by the various input substances. The natural gas and crude oil feedstock to produce chemicals were considered in terms of their higher heating values (HHV) along with the energy of the various fuels.

Table 4.8 gives the cumulative energy equivalent from cradle-to-product gate for the production of PF resin in terms of its fuel and feedstock sources in the ground. To produce 1.0 kg of resin it takes a total of 40.35 MJ of embodied energy based on the higher heating values of the various fuels and feedstock. Natural gas provides 50.9% of the energy, followed by crude oil at 37.2%, coal at 9.6%; and all other sources are of minor significance. As expected the natural gas use is high since it is used as fuel for both processing and electricity and as feedstock, and the crude is high since it is used as fuel for electricity and as feedstock for phenol.

Table 4.8. A breakdown by fuel and feedstock source to produce 1.0 kg PF resin at 47.4% solids cradle-to-product gate.

Energy use by fuel source	Energy[1] MJ/kg resin	Contribution %
Coal in ground	3.88E+00	9.6
Crude oil in ground	1.50E+01	37.2
Natural gas in ground	2.05E+01	50.9
Uranium in ground	6.66E-01	1.6
Wood fuel	1.83E-03	0.0
Electricity from other gases	7.18E-03	0.0
Electricity from other renewables	4.13E-02	0.1
Energy, from hydro power	1.22E-01	0.3
Energy, gross calorific value, in biomass	3.98E-02	0.1
Energy, potential (hydropower reservoir), converted	3.32E-02	0.1
TOTAL	40.35	100.0

[1] Electricity at 3.6 MJ/kWh, uranium at 381,000 MJ/kg and other fuels at their higher heating value (HHV) of coal 26.2 MJ/kg, crude oil 45.5 MJ/kg, natural gas 54.4 MJ/kg, and wood 20.9 MJ/kg.

Energy equivalence based on the input fuel component to manufacture PF resin can be of value in assessing the major contributors and for identifying opportunities for reducing energy use. Table 4.9 gives the embodied energy breakdown for manufacturing PF resin from in-ground resources to the output gate of the resin plant. The total energy is 40.35 MJ/kg resin with the phenol and the methanol providing the major contributions of 68.8% and 23.0% respectively, with contributions of 5.63% by sodium hydroxide, and all other contributors are of lesser significance. Transportation of chemical inputs to the plant represents only 0.63% of the total energy. Energy to provide resin manufacturing process energy and electricity for heat and emissions control represents only 1.86% of the total.

Table 4.9. A breakdown of energy contributors to produce 1.0 kg of PF resin at 47.4% solids cradle-to-product gate (based on HHV of fuel).

Energy use by process component	Energy MJ/kg resin	Contribution %
Phenol	2.78E+01	68.8
Methanol	9.29E+00	23.0
Sodium hydroxide 50% solids	2.27E+00	5.63
Trailer diesel	6.26E-02	0.16
Diesel locomotive	1.91E-01	0.47
Natural gas process	4.21E-01	1.0
Natural gas equipment (surrogate propane)	1.26E-06	0.00
Electricity, USA average process	2.40E-01	0.60
Electricity, USA average emissions equipment	1.05E-01	0.26
TOTAL	40.35	100

4.7 Sensitivity Analysis

The sensitivity analysis involves examining the impact of varying an input parameter such as fuel to a process and examining the magnitude of the change of an output parameter such as resource use or carbon dioxide (fossil) emission. The magnitude of the impact is dependent on the input parameter and also on the output parameter of interest. Tables 4.10 and 4.11 show that the dominant contributors are input materials of phenol and methanol, a smaller contribution by the use of sodium hydroxide, and little if any contributions from other on-site inputs of fuel and electricity, and little if any contribution by transportation of chemicals to the resin plant.

Changing any of the two dominant parameters will have a significant impact on most resource uses and emissions whereas changes of other lesser parameters such as transportation fuels, plant input chemical sodium hydroxide, and on-site use of natural gas and electricity, will have little if any impact. An analysis of the sensitivity for UF resin which is similar to the PF contributors, showed that varying the input of urea to the process by +10%, resulted in proportional changes to the percentage of contribution of each raw material and emission ranging from 0 to an expected 10% for those substances that urea is the sole contributor. Therefore, a sensitivity analysis of PF resin is not needed since the results would be similar.

Table 4.10. Contribution by input parameter to use of raw materials for the manufacture of PF resin.

Substance	kg/kg resin	PF resin process	Process input chemicals			Transportation		PF process	
			Phenol	Methanol	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
		% contribution							
Aluminium, 24% in bauxite, 11% in crude ore, in ground	3.20E-05	0	4	95	1	0	0	0	0
Anhydrite, in ground	2.64E-06	0	100	0	0	0	0	0	0
Barite, 15% in crude ore, in ground	2.74E-04	0	0	0	100	0	0	0	0
Calcite, in ground	5.27E-03	0	15	1	85	0	0	0	0
Carbon dioxide, in air	1.64E-04	0	19	2	78	0	0	0	0
Clay, bentonite, in ground	2.78E-05	0	99	0	1	0	0	0	0
Clay, unspecified, in ground	3.92E-04	0	64	2	34	0	0	0	0
Coal, 26.4 MJ per kg, in ground	1.28E-01	0	51	4	38	0	0	0	6
Coal, brown, in ground	1.30E-03	0	1	2	97	0	0	0	0
Coal, hard, unspecified, in ground	1.94E-02	0	93	0	7	0	0	0	0
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.53E-06	0	54	46	0	0	0	0	0
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	3.90E-06	0	0	100	0	0	0	0	0
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	1.03E-06	0	0	100	0	0	0	0	0
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	5.13E-06	0	0	100	0	0	0	0	0
Dolomite, in ground	1.39E-06	0	99	1	0	0	0	0	0
Gas, mine, off-gas, process, coal mining/m3	9.78E-06	0	8	2	90	0	0	0	0
Gas, natural, 46.8 MJ per kg, in ground	2.28E-01	0	18	73	5	0	0	3	1
Gas, natural, in ground	1.49E-01	0	100	0	0	0	0	0	0
Gravel, in ground	2.55E-04	0	6	90	4	0	0	0	0
Iron, 46% in ore, 25% in crude ore, in ground	1.86E-04	0	97	3	0	0	0	0	0
Limestone, in ground	7.35E-03	0	51	4	38	0	0	0	6
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	2.02E-06	0	0	100	0	0	0	0	0
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	4.08E-06	0	0	100	0	0	0	0	0
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	5.27E-06	0	0	100	0	0	0	0	0
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.68E-06	0	47	51	3	0	0	0	0
Oil, crude, 42 MJ per kg, in ground	1.89E-02	0	42	12	17	0	20	0	2
Oil, crude, in ground	3.11E-01	0	100	0	0	0	0	0	0
Peat, in ground	6.05E-05	0	100	0	0	0	0	0	0
Sand, unspecified, in ground	3.21E-05	0	100	0	0	0	0	0	0
Shale, in ground	7.48E-06	0	100	0	0	0	0	0	0
Sodium chloride, in ground	1.04E-01	0	0	0	100	0	0	0	0
Sulfur, in ground	2.16E-05	0	100	0	0	0	0	0	0
Uranium, 2291 GJ per kg, in ground	5.46E-07	0	51	4	38	0	0	0	6
Uranium, in ground	1.20E-06	0	96	0	4	0	0	0	0
Water, cooling, unspecified natural origin/kg	1.60E-02	100	0	0	0	0	0	0	0
Water, cooling, unspecified natural origin/m3	4.37E+01	0	82	4	14	0	0	0	0
Water, lake	1.56E-04	0	29	6	66	0	0	0	0
Water, process, drinking	1.97E-01	0	0	100	0	0	0	0	0
Water, process, unspecified natural origin/kg	2.97E-01	100	0	0	0	0	0	0	0
Water, process, well, in ground	3.70E-02	100	0	0	0	0	0	0	0
Water, river	1.08E-01	0	76	3	22	0	0	0	0
Water, salt, ocean	1.54E-01	0	98	0	2	0	0	0	0
Water, salt, sole	2.41E-04	0	7	8	85	0	0	0	0
Water, unspecified natural origin/m3	4.79E-01	0	92	0	8	0	0	0	0
Water, well, in ground	7.20E-03	0	4	13	83	0	0	0	0
Wood and wood waste, 9.5 MJ per kg	1.75E-04	0	34	39	20	0	2	2	3
Wood, hard, standing	1.21E-05	0	1	3	96	0	0	0	0
Wood, soft, standing	6.88E-05	0	27	2	71	0	0	0	0
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	7.48E-06	0	0	100	0	0	0	0	0

Table 4.10. Contribution by input parameter to use of raw materials for the manufacture of PF resin (continued).

Substance			Process input chemicals			Transportation		PF process	
		PF resin process	Phenol	Methanol	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
	kg/kg resin	% contribution							
Electricity from other gases	7.18E-03	0	52	3	39	0	0	0	6
Electricity from other renewables	4.13E-02	0	52	3	39	0	0	0	6
Energy, from hydro power	1.22E-01	0	52	3	39	0	0	0	6
Energy, gross calorific value, in biomass	3.98E-02	0	97	0	3	0	0	0	0
Energy, kinetic (in wind), converted	5.34E-04	0	1	2	97	0	0	0	0
Energy, potential (in hydropower reservoir), converted	3.32E-02	0	87	1	12	0	0	0	0
Energy, solar, converted	7.77E-06	0	1	2	97	0	0	0	0

Table 4.11. Contribution by input parameter to air emissions for the manufacture of PF resin.

Emissions to air		PF resin process	Process input chemicals: Phenol	Methanol	Sodium hydroxide	Transportation: Diesel truck	Diesel rail	PF process: Natural gas	Electricity
	kg/kg resin	% contribution							
Aldehydes, unspecified	9.77E-06	0	41	11	7	10	31	0	1
Ammonia	4.64E-06	0	17	5	75	0	0	0	2
Benzene	4.52E-04	0	100	0	0	0	0	0	0
Carbon dioxide, biogenic	1.89E-03	0	78	7	14	0	0	0	0
Carbon dioxide, fossil	1.16E+00	0	71	12	13	0	1	2	2
Carbon monoxide	1.27E-03	0	26	55	7	3	5	3	1
Carbon monoxide, biogenic	1.65E-06	0	93	1	6	0	0	0	0
Carbon monoxide, fossil	7.36E-04	0	99	0	1	0	0	0	0
Chlorine	1.89E-06	0	0	2	97	0	0	0	0
Cumene	6.54E-04	0	100	0	0	0	0	0	0
Dimethyl ether	4.73E-06	100	0	0	0	0	0	0	0
Dinitrogen monoxide	2.86E-06	0	48	5	42	0	0	0	6
Ethene	1.82E-06	0	98	0	2	0	0	0	0
Formaldehyde	6.73E-06	99	0	0	0	0	0	0	0
Hydrocarbons, aliphatic, alkanes, cyclic	1.29E-06	0	100	0	0	0	0	0	0
Hydrocarbons, aromatic	8.38E-06	0	100	0	0	0	0	0	0
Hydrogen	4.09E-05	0	22	0	78	0	0	0	0
Hydrogen chloride	3.29E-05	0	64	3	29	0	0	0	4
Hydrogen fluoride	3.60E-06	0	55	4	36	0	0	0	6
Lead	2.87E-08	0	35	35	26	0	0	0	3
Mercury	1.21E-08	0	43	5	47	0	0	0	5
Methane	2.09E-03	0	28	53	14	0	0	2	2
Methane, biogenic	1.03E-05	0	83	0	17	0	0	0	0
Methane, fossil	4.50E-03	0	95	5	0	0	0	0	0
Methanol	1.14E-04	3	0	97	0	0	0	0	0
Nickel	1.41E-06	0	95	1	3	0	0	0	0
Nitrogen oxides	3.37E-03	0	57	18	16	1	4	2	2
NMVOC, non-methane volatile organic compounds, unspecified origin	3.05E-03	0	40	50	4	0	2	2	1
Organic substances, unspecified	6.00E-05	0	49	4	9	32	6	0	0
Particulates	2.31E-06	100	0	0	0	0	0	0	0
Particulates, < 10 um	1.52E-04	0	46	5	17	3	25	1	3
Particulates, < 2.5 um	4.16E-05	0	96	1	3	0	0	0	0
Particulates, > 10 um	5.58E-05	0	92	1	7	0	0	0	0
Particulates, > 2.5 um, and < 10um	7.00E-05	0	98	1	1	0	0	0	0
Particulates, unspecified	3.33E-04	0	50	6	37	0	0	0	6
Phenol	2.05E-06	99	0	0	0	0	0	0	0
Propene	2.42E-04	0	100	0	0	0	0	0	0
Sulfur dioxide	1.26E-03	0	98	1	2	0	0	0	0
Sulfur oxides	9.80E-03	0	25	59	11	0	0	3	2
VOC, volatile organic compounds	2.89E-05	100	0	0	0	0	0	0	0
	MJ/kg resin								
Heat, waste	9.22E+00	0	80	11	9	0	0	0	0
	Bq/kg resin								
Noble gases, radioactive, unspecified	9.40E+02	0	2	2	96	0	0	0	0
Radioactive species, unspecified	6.28E+03	0	53	4	37	0	0	0	6
Radon-222	1.77E+03	0	2	2	96	0	0	0	0

4.8 Carbon Content And Footprint of pf Resin

When it comes to climate change and related issues as a result of increased greenhouse gas emissions to the atmosphere, two topics are of interest: 1) the amount of carbon store in a material that can in some instances be considered as an offset when sequestered near-term to reduce the amount of CO_2 emissions to the atmosphere, and 2) the carbon footprint of a material that gives the amount of greenhouse gases such as CO_2 released to the atmosphere during its life cycle. The sum of the two values with carbon store as a negative value gives the net CO_2 impact of a material upon the environment.

Cured PF resin is comprised of 59.5% of carbon by weight for 0.595 kg/kg resin 100% solids (Broline 2008). The percentage is based on in-mill additives and no loss of formaldehyde. The carbon content is an estimate which can vary with changes in formulation and resin mix. Unfortunately this carbon cannot be considered as a carbon store offset to CO_2 emissions since it is not continuously renewing in the carbon cycle. The resin carbon was sequestered hundreds of million years ago during the formation of the fossil fuels that are used as its feedstock. The carbon in the resin is unlike the carbon stored in trees and wood which was sequestered near-term within the last 30-100 years, is part of a continuously renewing carbon cycle, and can be counted as an offset against emissions of CO_2 to the atmosphere when looking at a materials carbon footprint and impact upon global warming.

The carbon footprint is determined by the CO_2 equivalent of all greenhouse gas (GHG) emissions during the life cycle of a product, in this case from resources in the ground through extractions, deliveries and manufacturing of the liquid PF resin. The CO_2 equivalent of each GHG can be determined by multiplying its comparative reactive factor in the atmosphere to that for carbon dioxide based on a 100-year time horizon (IPCC 2007). There are three GHGs that normally occur for the life cycle of wood products—CO_2 (fossil fuel contributions), CH_4 (methane), and N_2O (listed as nitrous oxide and dinitrogen oxide in the LCI output), other GHGs such as CFC do not make a significant contribution. The total carbon footprint for the life cycle of PF resin from cradle-to-gate is given by the following—the emission value of each contribution is given in Table 4.6:
Carbon Footprint kg-CO_2 eq = CO_2 kg + (CH_4 kg x 25) + (N_2O kg x 298)

The carbon footprint in kg-CO_2 equivalent (eq) is determined by the mass of each contributor times how reactive it is in comparison to CO_2 in the atmosphere, e.g., CH_4 (methane) is 25 times more reactive than CO_2 and N_2O (nitrous oxide) is 298 times more reactive than CO_2. Considering the total emissions from cradle-to-product gate for each of these contributors gives a total of 2.7884 kg-CO_2 eq. per kg of 100% solids PF resin, see Table 4.12. These emissions are generated in the process of extracting the fuel and feedstock, generation of electricity, delivery of fuel and feedstock, and the combustion fuel in the manufacture of the resin.

Table 4.12. The carbon footprint given in kg-CO2 equivalent (eq) for 100% solids PF resin.

Greenhouse gas (GHG)	GHG Contribution kg/kg resin 47.4% solids	CO_2 equiv. multiplier	Carbon Footprint kg-CO_2 eq/kg resin 100% solids
CO_2	1.16	1	2.4387
Methane (CH_4)	0.00660	25	0.3479
Nitrous oxide (N_2O)	0.00000286	298	0.0018
Total			2.7884

4.9 Study Discussion

The data documented in this chapter on the manufacture of PF resin forms a foundation for the scientific assessment of its environmental performance. The PF resin data should not be considered as a stand alone product; rather it should be used when conducting life-cycle inventories and assessments of wood composite products that use this resin as a bonding agent during their manufacture. Resins are an integral component and contributor to the performance of wood composites. A life-cycle assessment of the use of resins in composites can be used in a number of ways to show their favorable performance for such environmental issues as sustainability, global warming, climate change, carbon footprint, carbon storage, carbon trading and caps, carbon taxes, green purchasing, and green building. The data can be used as stated or in a life-cycle assessment to compare wood composite products to various competitive materials or assemblies of various materials. Individual LCI data of PF resin can be used as a benchmark for process or product improvements or for comparing performance to those of other materials but it is important to make comparisons on an equal product performance basis since resin efficiency varies by resin type.

4.10 Conclusion

A cradle-to-product gate life-cycle inventory (LCI) study was conducted of manufacturing 1.0 kg of phenol-formaldehyde (PF) resin at 47.4% solids—the LCI functional unit for this study—in the U.S. The study covered data analyses from the raw resources in the ground through resin manufacturing for the production year 2005. Production data was collected by survey of resin manufacturers representing 62% of total U.S. production of PF resin for the plywood, laminated veneer lumber (LVL), and hardboard industries that annually used about 779 million kg of PF resin at 47.4% solids. Secondary LCI data from the Franklin Associates Limited and Ecoinvent databases were used for input chemicals, fuels, electricity and transportation. Ecoinvent data was adjusted to U.S. fuels, electricity, and transportation values where appropriate.

The quality of the LCI data collected for the manufacture of PF resin was high as judged by assessments for similarity of values, molar ratio of formaldehyde to phenol, and the mass flow of material in and out of the process. Any data questions were resolved by re-contacting the manufacturers that participated in the survey. The molar ratio of formaldehyde to phenol was found to be 2.23 within the expected range of 2.00 to 2.25.

Assigning of environmental burden in the production of PF resin was entirely to the product since no co-products were produced during the process. For the output functional unit of 1.0 kg of PF resin at 47.4% solids, the main input components were phenol of 0.244 kg, methanol at 0.209 kg, sodium hydroxide at 0.061 kg, and water at 0.349 kg for resin and processing use. Methanol is used in a reactor to produce formaldehyde which is then used with the addition of phenol and some sodium hydroxide in a second reactor to produce the PF resin. Additional water to make the resin occurs during the condensation polymerization in the reactor.

Environmental impacts were assessed for those at the resin manufacturing site (referred to as on-site emissions) and those for cradle-to-product gate which begins with resources in the ground through extraction, generation, delivery, and resin manufacture. On-site impacts are generally small compared to the cradle-to-product gate impacts, with less use of resources and lesser emissions. Per 1.0 kg of liquid resin the on-site energy use of 0.443 MJ/kg compared to 40.35 MJ/kg neat resin for cradle-to-product gate, and emissions to air such as CO_2, CO, VOC, particulate, formaldehyde, methanol, and phenol are 1%, 1%, 100% (cradle-to-gate chemicals only consider individual VOC contributions and not as a grouping), 1%, 99% (formaldehyde and PF resin manufacture occur on-site), 3% and 99% (phenol emissions occur due to PF resin manufacture on-site) of the cradle-to-gate values, in addition there are many more substance type emissions for cradle-to-gate than on-site. The on-site emissions to water were also smaller. Even water use was much less at only 1% of cradle-to-product gate values. Overall the resin manufacturing operations are resource efficient and relatively friendly to the environment.

In terms of energy equivalent for fuels and feedstock from cradle-to-gate, the manufacture of phenol and methanol from in-ground fuel resources contributed to 68.8%, and 23.0% respectively, whereas the sodium hydroxide contributed 5.63% of the total energy. The transportation of chemical inputs to the resin plants, and on-site processing fuels and electricity, were all minor contributors to the total energy.

A sensitivity of the input parameters to the output use of materials and emissions to air, water, and land are likewise dominated by input phenol and methanol chemicals. Other inputs of on-site fuel and electricity use, and transportation of chemicals to the plant, all are minor contributors. Changing the input value of phenol and/or methanol would result in expected proportional outputs of emissions; changes in other minor parameters would generally result in no significant changes in output.

The carbon footprint from cradle-to-gate to produce PF resin is 2.7884 kg-CO_2 eq per 1.0 kg of 100% solids resin. The carbon footprint accounts for all greenhouse gas emissions during the life cycle of a product, in this case from cradle-to-gate. Although PF cured resin has a carbon component of 59.5%, it is not considered as an offset for CO_2 emissions to the atmosphere during processing since its carbon was not sequestered near-term and it is not a continuously renewing carbon cycle.

To benefit from the availability of the LCI database for PF resin, the following additional studies are recommended: 1) extract pertinent data that documents the favorable environmental performance of PF resin and 2) edit prior CORRIM LCI studies that used PF resin to include the LCI data developed in this study.

5.0 Life-Cycle Inventory of Phenol-Resorcinol-Formaldehyde Resin

5.1 Introduction

5.1.1 Survey Data

The phenol-resorcinol-formaldehyde (PRF) resin survey data was for 8 plants in U.S. that represented 63% of total production for the year 2005. Total annual production was 34,166,667 lbs (15,513,000 kg) of neat resin at 60% non-volatile solids content. PRF production is small in comparison to that for PF resin; it is only a little over 1% of PF annual production. PRF total production is based on its use for glue laminated beams (glulam) and composite I-joists as given by CORRIM data (Puettmann and Wilson 2005, and Wilson and Dancer 2005b). PRF resins differ somewhat from the other resins in that to assist curing when producing wood composites they use a hardener—predominately paraformaldehyde for manufacturing glue laminated timbers and oxazolidine for manufacturing I-joists. As a group, 60% of PRF adhesive use paraformaldehyde and 40% use oxazolidine. PFR resin can be cold or hot cured, and can be radio-frequency cured.

5.1.2 Materials Flow

Those materials considered in the LCI analysis of PRF resin production included those listed in Table 5.1. The process is similar to the production of PF resin except that in addition to phenol, resorcinol is also reacted with the formaldehyde in the second reactor. Input materials considered were phenol, resorcinol, methanol, ethanol, sodium hydroxide, and water. The silver or molybdenum/iron oxide catalyst used to produce formaldehyde from methanol was not included in the analysis because it is a small contributor to the analysis and the manufacturers considered this information proprietary.

Table 5.1. Listing of input chemicals used to produce phenol-resorcinol-formaldehyde (PRF) resin.

Input Material	Product
Phenol (100%)[1]	Phenol-resorcinol-formaldehyde resin (60%)[2]
Resorcinol (100%)	
Methanol (100%)	
Ethanol (100%)	
Sodium hydroxide (50%)	
Water	

[1] Solids content or solution strength of chemicals into the plant.

[2] Solids content of resin out of the plant.

5.1.3 Transportation

The delivery of chemicals to the resin plants is by both truck and rail. Table 5.2 gives the one-way deliver distances. Usually the truck deliveries have no back haul of other materials. The t·km (the mass (t for tonne) times distance traveled (km)) values are used in the SimaPro software by accessing the FAL database to obtain U.S. typical environmental impacts for truck and rail transportation. Other chemicals are used in the resin production process but their quantity and contribution to environmental impacts were so insignificant that they were not included in either the input data or the transportation calculations.

Table 5.2. One-way delivery distance for input chemicals to PRF resin plants.

	Transportation		One-way distance	Chemical weight		Truck	Rail
Chemical	**mode**	**% mode**	**km**	**kg**	**t**	**tkm**	**tkm**
Phenol	truck	12	84	0.277	2.77E-04	2.86E-03	
Phenol	rail	88	2,507	0.277	2.77E-04		6.09E-01
Resorcinol	truck	100	4,344	0.190	1.90E-04	8.26E-01	
Methanol	truck	12	421	0.103	1.03E-04	5.37E-03	
Methanol	rail	88	2,026	0.103	1.03E-04		1.83E-01
Ethanol	truck	100	143	0.007	7.00E-06	9.98E-04	
NaOH	truck	100	143	0.008	8.00E-06	1.14E-03	
Total						8.37E-01	7.92E-01

5.2 Product Yields

The inputs to produce 1.0 kg of neat phenol-resorcinol-formaldehyde (PRF) resin at 60% non-volatile solids content consist of the three primary chemicals of phenol at 0.277 kg, resorcinol at 0.190 kg, and methanol at 0.103 kg; also used were lesser amounts of ethanol at 0.00744 kg and sodium hydroxide at 0.00372 kg, and 0.656 kg of water. A significant portion of the processing water is recycled back into the resin. See Table 5.3 for a listing of all inputs and outputs except emissions for the manufacture of PRF resin. Electricity is used for processing by fans and pumps, and for operating emissions control equipment, while the natural gas is used for boiler fuel and emission control equipment, and propane is used for fuel in forklifts.

Table 5.3. Inputs for the production of 1.0 kg of PRF resin at 60% solids.

	SI Unit	Unit/kg PRF 60% solids
INPUTS		
Chemicals[1]		
Phenol	kg	2.77E-01
Resorcinol	kg	1.90E-01
Methanol	kg	1.03E-01
Ethanol	kg	7.44E-03
Sodium hydroxide (50%)	kg	3.72E-03
Water[2]		
Water, municipal	kg	4.61E-01
Water, well source	kg	1.95E-01
Elecctricity and fuel use		
Electricity	kWh	8.30E-02
Electricity for emissions control	kWh	1.59E-02
Natural gas	m^3	3.18E-02
Propane	L	2.50E-05
OUTPUTS[3]		
PRF liquid resin (60% solids)	kg	1.0

[1] All chemical weights given at either 100% non-volatile solids or dry except for PRF resin given on a 60% solids basis.

[2] There is a significant amount of water recycling back into the resin.

[3] Emissions to air, water and land listed in separate table.

The molar ratio of formaldehyde to phenol plus resorcinol was used as a check on the quality of the data. Assuming that it takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde, the molar ratio of formaldehyde to phenol plus resorcinol for this representative resin system was determined to be 0.61 which is as expected less than 1.0 for a contemporary commercial PRF resin for use in the glulam industry. The value of the molar ratio affects both the performance of the resin and the properties of the composite timber made with this resin.

5.3 Manufacturing Energy Summary

5.3.1 Sources of Energy and Electricity

Energy for the production of PRF resin comes from electricity to operate fans and pumps, natural gas to generate steam (boiler) for heating reactors and input chemicals, and propane gas (LPG) to operate forklift equipment. Electricity and natural gas are also used to operate regenerative thermal oxidizers (RTOs) and regenerative catalytic oxidizers (RCOs) at some plants to control air emissions. A breakdown by fuel sources for the production of electricity for the U.S. in 2005 was given previously in Table 1.1.

Natural gas is the primary fuel in resin manufacturing; it is used for generating steam that is used to heat input chemicals and reactors; and is used for combusting VOCs and HAPs in RTO and RCO emission control systems. The natural gas and/or electricity use would have been slightly greater had all resin plants used RTO and RCO emissions control devices. In addition to natural gas use, a small amount of propane fuel was used to operate fork lift trucks and handlers within the plant. Electricity is used to operate fans and blowers. Table 5.4 gives the energy use on-site for manufacturing PRF resin. The natural gas provides 77.4% of the energy and the electricity provides 22.6%. The propane is an insignificant contributor to the energy use.

Table 5.4. O On-site fuel and electricity use in terms of their energy equivalence for the manufacture of 1.0 kg of PRF resin at 60% non-volatile solids.

Energy use[1]	Unit	Unit/kg PRF resin	MJ/kg PRF resin	% Use
Electricity process	MJ	2.99E-01	2.99E-01	19.0
Electricity emissions control	MJ	5.71E-02	5.71E-02	3.6
Natural gas	m^3	3.18E-02	1.22E+00	77.4
Propane	L	2.50E-05	9.51E-07	0.0
Total energy			1.58	100.0

[1] Electricity at 3.6 MJ/kWh and fuels at their higher heating value (HHV) of natural gas at 54.4 MJ/kg and propane at 54.0 MJ/kg.

5.4 Plant Emissions for Producting PRF Resin

Outputs for the production of 1.0 kg of PRF resin at 60% solids include emissions to air, water and land, see Table 5.5. Emissions are generated due to emissions of the combustion of gases and the chemical reactions in the reactors. For combustion, only CO_2 and CO are given—both were calculated using the SimaPro software, actual gas use, and the Franklin database for U.S. fuels—the total emissions are determined by considering natural gas and propane on-site fuel use. All other emissions were collected by survey; they include emissions to air of particulate, volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) of formaldehyde, methanol, and phenol that come off of the absorber and the reactor. The emissions of dimethyl ether (DME) were below the cut-off value since most PRF production facilities used the silver oxide process which does not produce measurable amounts of DME.

Table 5.5. On-site reported outputs for the production of 1.0 kg of PRF resin at 60% non-volatile solids.

	Survey Wt. Average kg/kg PRF 60% solids
Production output	
Phenol-resorcinol-formaldehyde resin (60% solids)	1.00
Emissions to air[1]	
CO_2[2], fossil (GHG)[3]	6.85E-02
CO[2]	1.49E-04
VOC	3.38E-05
Particulate	3.01E-06
Formaldehyde (HAP)[3]	8.80E-06
Methanol (HAP)[3]	5.20E-06
Phenol (HAP)[3]	4.16E-06
Emissions to water	
BOD	2.81E-03
TSS	1.67E-04
Phenol	1.14E-04
Formaldehyde	3.32E-04
Emissions to land[1]	
Solids	1.65E-04

[1] Emissions data reported in survey.

[2] CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant.

[3] HAP hazardous air pollutant; GHG greenhouse gas.

5.5 Cradle-to-Product Gate Process Related Resource Use and Emissions

The life-cycle inventory for the production of PRF resin covers its cycle from in-ground resources through the production and delivery of input chemicals and fuels, through its manufacture of a resin as shipped to the customer. It examines the use of all resources, fuels and electricity and all emissions to air, water and land; it also includes feedstock of natural gas and crude oil used to produce some of the chemicals. Table 5.6 gives the raw materials and energy sources, and Table 5.7 gives emissions to air, water and land for the cradle-to-gate inventory. The cradle-to-gate impacts for resorcinol were not included since none of the databases, including Ecoinvent in SimaPro, had a LCI database that could be used. The resorcinol in the output was listed as a raw material resource—a substance. The raw materials in the ground include coal, natural gas, limestone, crude oil, and uranium, water usage and others. Materials of quantities smaller than 1.0E-06 kg/kg are not included in the listing. Because life-cycle studies involve tracing resource use back to its in-ground resources, some materials or substances can involve many steps of backtracking to their source, resulting in the use of a large numbers of substances, many of insignificant quantity. For this study a filter was used to remove insignificant substances from the listing. The filter varied depending on whether the emission was to air, water, or land. The exception was for substances that are highly toxic such as uranium and mercury that occur during the generation of electricity where values less than the cut-off value are shown.

Some sources of energy or fuels cannot be traced back to their original resource in the ground. Such energies include "energy from hydro power," "electricity from other gases" and "electricity from renewables" which are not defined in terms of identifiable fuels are listed in a separate category defined as Energy and are given in MJ/kg of resin.

Emissions for the cradle-to-gate scenario are listed in Table 5.7. The emissions to air and water used a cut-off value of 1.0E-06 kg/kg resin, and radiation type emissions had a cut-off of 1.0E+00 Bq/kg resin. Emissions to land used a cut-off of 1.0E-06 kg/kg resin. Some emissions because of their toxicity, even though in quantities below the cut-off value, are also shown. Raw materials and emissions for a cradle-to-product gate inventory are far greater in general than those resources and emissions that occur at the production site, this is true for all processes. The difference between on-site and cradle-to-product gate resource use can be found by comparing Tables 5.3 and 5.6, and emission difference by comparing Tables 5.5 and 5.7.

Table 5.6. LCI output of allocated, cumulative raw material use cradle-to-product gate for the production of 1.0 kg of PRF resin at 60% solids.

Raw material	kg/kg resin
Aluminium, 24% in bauxite, 11% in crude ore, in ground	1.65E-05
Anhydrite, in ground	3.02E-06
Barite, 15% in crude ore, in ground	1.81E-05
Calcite, in ground	1.19E-03
Carbon dioxide, in air	5.21E-05
Clay, bentonite, in ground	3.16E-05
Clay, unspecified, in ground	3.00E-04
Coal, 26.4 MJ per kg, in ground	1.05E-01
Coal, brown, in ground	1.71E-04
Coal, hard, unspecified, in ground	2.10E-02
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.29E-06
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	1.92E-06
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	2.53E-06
Dolomite, in ground	1.58E-06
Gas, mine, off-gas, process, coal mining/m3	3.12E-06
Gas, natural, 46.8 MJ per kg, in ground	1.67E-01
Gas, natural, in ground	1.72E-01
Gravel, in ground	1.32E-04
Iron, 46% in ore, 25% in crude ore, in ground	2.10E-04
Limestone, in ground	6.08E-03
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in grd	2.01E-06
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.60E-06
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.33E-06
Oil, crude, 42 MJ per kg, in ground	3.51E-02
Oil, crude, in ground	3.57E-01
Olivine, in ground	1.02E-06
Peat, in ground	7.01E-05
Phosphorus, 18% in apatite, 4% in crude ore, in ground	1.47E-06
Resorcinol	1.90E-01
Sand, unspecified, in ground	3.67E-05
Shale, in ground	8.56E-06
Sodium chloride, in ground	7.04E-03
Sulfur, in ground	2.49E-05
Uranium, 2291 GJ per kg, in ground	4.52E-07
Uranium, in ground	1.32E-06
Water, cooling, unspecified natural origin/m3	4.20E+01
Water, lake	1.19E-03
Water, process, drinking	9.72E-02
Water, process, well, in ground	2.00E-01
Water, river	1.02E-01
Water, salt, ocean	1.73E-01
Water, salt, sole	1.81E-04
Water, unspecified natural origin/kg	4.60E-01
Water, unspecified natural origin/m3	8.23E+00
Water, well, in ground	3.89E-03
Wood and wood waste, 9.5 MJ per kg	1.50E-04
Wood, hard, standing	1.77E-06
Wood, soft, standing	2.65E-05
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	3.69E-06
	MJ/kg resin
Electricity from other gases	5.92E-03
Electricity from other renewables	3.41E-02
Energy, from hydro power	1.01E-01
Energy, gross calorific value, in biomass	4.44E-02
Energy, kinetic (in wind), converted	7.10E-05
Energy, potential (in hydropower reservoir), converted	3.41E-02
Energy, solar, converted	1.22E-06

Table 5.7. LCI output of allocated, cumulative emissions cradle-to-product gate for the production of 1.0 kg of PRF resin at 60% solids.

Emissions to air	kg/kg resin
Aldehydes, unspecified	2.36E-05
Ammonia	1.66E-06
Benzene	5.13E-04
Carbon dioxide, biogenic	1.84E-03
Carbon dioxide, fossil	1.23E+00
Carbon monoxide	1.52E-03
Carbon monoxide, biogenic	1.79E-06
Carbon monoxide, fossil	8.34E-04
Cumene	7.42E-04
Dinitrogen monoxide	2.24E-06
Ethene	1.08E-05
Formaldehyde	8.83E-06
Hydrocarbons, aliphatic, alkanes, cyclic	1.46E-06
Hydrocarbons, aromatic	9.69E-06
Hydrogen	1.24E-05
Hydrogen chloride	2.98E-05
Hydrogen fluoride	3.05E-06
Lead	2.08E-08
Mercury	8.55E-09
Methane	1.58E-03
Methane, biogenic	9.94E-06
Methane, fossil	5.02E-03
Methanol	5.98E-05
Nickel	1.56E-06
Nitrogen oxides	3.70E-03
NMVOC, non-methane volatile organic compounds, unspecified origin	2.80E-03
Organic substances, unspecified	3.24E-04
Particulates	3.01E-06
Particulates, < 10 um	2.19E-04
Particulates, < 2.5 um	4.63E-05
Particulates, > 10 um	6.00E-05
Particulates, > 2.5 um, and < 10um	7.93E-05
Particulates, unspecified	2.78E-04
Phenol	4.17E-06
Propene	2.75E-04
Sulfur dioxide	1.42E-03
Sulfur oxides	7.49E-03
VOC, volatile organic compounds	3.38E-05
	MJ/kg resin
Heat, waste	9.08E+00
	Bq/kg resin
Noble gases, radioactive, unspecified	1.44E+02
Radioactive species, unspecified	4.98E+03
Radon-222	3.04E+02

Emissions to water	kg/kg resin
Aluminum	6.17E-05
Ammonium, ion	1.42E-06
Antimony	1.90E-06
Benzene	1.22E-03
BOD5, Biological Oxygen Demand	1.42E-02
Boron	1.05E-05
Bromate	1.05E-06
Bromine	1.66E-06
Calcium, ion	7.56E-05
Carbonate	3.78E-05
Chlorate	8.06E-06
Chloride	5.87E-04
Chromium VI	1.05E-06
COD, Chemical Oxygen Demand	1.17E-02
Copper, ion	1.52E-06
Cumene	1.78E-03
DOC, Dissolved Organic Carbon	3.42E-03
Fluoride	3.10E-06
Formaldehyde	3.42E-04
Hydrocarbons, unspecified	6.57E-06
Iron	1.44E-05
Iron, ion	9.47E-06
Lead	3.69E-07
Magnesium	7.62E-06
Manganese	8.48E-06
Mercury	7.84E-09
Methanol	3.09E-06
Nitrate	3.76E-06
Oils, unspecified	1.68E-04
Organic substances, unspecified	2.72E-05
Phenol	1.15E-04
Phosphate	1.96E-05
Phosphorus	1.06E-06
Potassium, ion	9.38E-05
Propene	6.57E-04
Silicon	2.57E-04
Sodium, ion	1.27E-04
Solids, inorganic	9.25E-06
Solved solids	8.86E-03
Sulfate	7.56E-04
Sulfuric acid	2.54E-06
Suspended solids, inorganic	1.67E-04
Suspended solids, unspecified	3.01E-04
TOC, Total Organic Carbon	3.43E-03
Zinc, ion	2.05E-06
	MJ/kg resin
Heat, waste	4.37E-02
	Bq/kg resin
Hydrogen-3, Tritium	6.44E+00

Emissions to land	kg/kg resin
Solids	1.65E-04
Waste, solid	6.30E-02

5.6 Cradle-To-Product Gate Resource Use for Embodied Energy

The embodied energy to produce PRF resin can be given in several formats. For this study it is useful to examine the energy breakdown in terms of both its source of fuel and feedstock in the ground and its contribution by the various input substances. The natural gas and crude oil feedstock to produce chemicals was considered in terms of their higher heating value (HHV) along with the energy of the various fuels.

Table 5.8 gives the cumulative energy equivalent from cradle-to-product gate for the production of PRF resin in terms of its fuel and feedstock source in the ground. To produce 1.0 kg of resin it takes a total of 40.45 MJ of embodied energy based on the HHVs of the various fuels and feedstock. Natural gas provides 45.5% of the energy, followed by crude oil at 44.1%, coal at 8.2%; and all other sources are of minor significance. Natural gas and crude oil are used directly or indirectly as feedstock or fuel for the production of phenol, resorcinol, and methanol (as such formaldehyde); therefore, greater use is expected in the LCI output.

Table 5.8. A breakdown by fuel and feedstock source to produce 1.0 kg PRF resin at 60% solids cradle-to-product gate.

Energy use by fuel source	Energy[1] MJ/kg resin	Contribution %
Coal in ground	3.32E+00	8.2
Crude oil in ground	1.78E+01	44.1
Natural gas in ground	1.84E+01	45.5
Uranium in ground	6.76E-01	1.7
Wood fuel	1.56E-03	0.0
Electricity from other gases	5.92E-03	0.0
Electricity from other renewables	3.41E-02	0.1
Energy, from hydro power	1.01E-01	0.2
Energy, gross calorific value, in biomass	4.44E-02	0.1
Energy, potential (in hydropower reservoir), converted	3.41E-02	0.1
TOTAL	40.45	100.0

[1] Electricity at 3.6 MJ/kWh, uranium at 381,000 MJ/kg and other fuels at their higher heating value (HHV) of coal 26.2 MJ/kg, crude oil 45.5 MJ/kg, natural gas 54.4 MJ/kg, and wood 20.9 MJ/kg.

Energy equivalence by the input fuel component to the manufacturing can be of value in assessing the major contributors and for identifying opportunities for reducing energy use. Table 5.9 gives the embodied energy breakdown for manufacturing PRF resin from in-ground resources to the output gate of the resin plant. The total embodied energy is 40.45 MJ/kg resin with the phenol and the methanol providing the major contributions of 77.9% and 11.3% respectively, and all other contributors are of lesser significance. Since resorcinol was considered from nature and not modeled back to its in-ground resources because of a lack of an available database, it had no energy contribution. Transportation of chemical inputs to the plants represents only 2.85% of the total energy. Energy to provide resin manufacturing process energy from natural gas combustion and electricity for heat and emissions control represents only 6.72% of the total. More on-site processing energy is needed than for the production of PF resin.

Table 5.9. A breakdown of energy contributors to produce 1.0 kg of PRF resin at 60% solids cradle-to-product gate (based on HHV of fuel).

Energy use by process component	Energy MJ/kg resin	Contribution %
Phenol	3.15E+01	77.9
Resorcinol	-	-
Methanol	4.58E+00	11.3
Ethanol	3.29E-01	0.8
Sodium hydroxide 50% solids	1.49E-01	0.37
Trailer diesel	9.29E-01	2.30
Diesel locomotive	2.24E-01	0.55
Natural gas process	1.64E+00	4.1
Natural gas equipment (surrogate propane)	1.28E-06	0.00
Electricity, USA average process	9.05E-01	2.24
Electricity, USA average emissions equipment	1.73E-01	0.43
TOTAL	40.45	100

5.7 Sensitivity Analysis

The sensitivity analysis involves examining the impact of varying an input parameter such as fuel to a process and examining the magnitude of the change of an output parameter such as resource use or carbon dioxide (fossil) emission. The magnitude of the impact is dependent on the input parameter and also on the output parameter of interest. Tables 5.10 and 5.11 show that the dominant contributors are input materials of phenol and methanol, a smaller contribution by the use of sodium hydroxide, and little if any contributions from other on-site inputs of fuel and electricity, and little if any contribution by transportation of chemicals to the resin plant.

Changing any of the two dominant parameters will have a significant, yet proportional impact on most resource uses and emissions whereas changes of other lesser parameters such as transportation fuels, plant input chemical sodium hydroxide, and on-site use of natural gas and electricity, will have little if any impact. An analysis of the sensitivity for UF resin which is somewhat similar to the PRF contributors, showed that varying the input of urea to the process by +10%, resulted in proportional changes to the percentage of contribution of each raw material and emission ranging from 0 to an expected maximum of 10% for those substances that urea is the sole contributor. Therefore, a sensitivity analysis of PRF resin is not needed since the results would be similar.

Table 5.10. Contribution by input parameter to use of raw materials for the manufacture of PRF resin.

Substance			Process input chemicals					Transportation		PF process	
		PF resin process	Phenol	Resorcinol	Methanol	Ethanol	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
	kg/kg resin	% contribution									
Aluminium, 24% in bauxite, 11% in crude ore, in ground	1.65E-05	0	9	0	91	0	0	0	0	0	0
Anhydrite, in ground	3.02E-06	0	99	0	0	1	0	0	0	0	0
Barite, 15% in crude ore, in ground	1.81E-05	0	0	0	1	0	99	0	0	0	0
Calcite, in ground	1.19E-03	0	73	0	1	1	25	0	0	0	0
Carbon dioxide, in air	5.21E-05	0	69	0	4	11	16	0	0	0	0
Clay, bentonite, in ground	3.16E-05	0	99	0	0	1	0	0	0	0	0
Clay, unspecified, in ground	3.00E-04	0	95	0	2	1	3	0	0	0	0
Coal, 26.4 MJ per kg, in ground	1.05E-01	0	70	0	3	0	3	0	0	0	24
Coal, brown, in ground	1.71E-04	0	7	0	8	37	48	0	0	0	0
Coal, hard, unspecified, in ground	2.10E-02	0	98	0	0	2	0	0	0	0	0
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	1.29E-06	0	73	0	27	0	0	0	0	0	0
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	1.92E-06	0	0	0	100	0	0	0	0	0	0
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	2.53E-06	0	0	0	100	0	0	0	0	0	0
Dolomite, in ground	1.58E-06	0	99	0	0	1	0	0	0	0	0
Gas, mine, off-gas, process, coal mining/m3	3.12E-06	0	30	0	3	49	18	0	0	0	0
Gas, natural, 46.8 MJ per kg, in ground	1.67E-01	0	29	0	49	0	0	1	0	18	3
Gas, natural, in ground	1.72E-01	0	99	0	0	1	0	0	0	0	0
Gravel, in ground	1.32E-04	0	14	0	86	0	1	0	0	0	0
Iron, 46% in ore, 25% in crude ore, in ground	2.10E-04	0	98	0	1	1	0	0	0	0	0
Limestone, in ground	6.08E-03	0	70	0	3	0	3	0	0	0	24
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	2.01E-06	0	0	0	100	0	0	0	0	0	0
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	2.60E-06	0	0	0	100	0	0	0	0	0	0
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	1.33E-06	0	67	0	32	1	0	0	0	0	0
Oil, crude, 42 MJ per kg, in ground	3.51E-02	0	26	0	3	0	1	53	13	1	4
Oil, crude, in ground	3.57E-01	0	99	0	0	1	0	0	0	0	0
Olivine, in ground	1.02E-06	0	99	0	0	1	0	0	0	0	0
Peat, in ground	7.01E-05	0	98	0	0	2	0	0	0	0	0
Phosphorus, 18% in apatite, 4% in crude ore, in ground	1.47E-06	0	0	0	1	99	0	0	0	0	0
Resorcinol	1.90E-01	0	0	100	0	0	0	0	0	0	0
Sand, unspecified, in ground	3.67E-05	0	99	0	0	1	0	0	0	0	0
Shale, in ground	8.56E-06	0	99	0	0	1	0	0	0	0	0
Sodium chloride, in ground	7.04E-03	0	2	0	0	0	97	0	0	0	0
Sulfur, in ground	2.49E-05	0	99	0	0	1	0	0	0	0	0
Uranium, 2291 GJ per kg, in ground	4.52E-07	0	70	0	3	0	3	0	0	0	24
Uranium, in ground	1.32E-06	0	98	0	0	1	0	0	0	0	0
Water, cooling, unspecified natural origin/m3	4.20E+01	0	97	0	2	1	1	0	0	0	0
Water, lake	1.19E-03	0	4	0	0	95	1	0	0	0	0
Water, process, drinking	9.72E-02	0	0	0	100	0	0	0	0	0	0
Water, process, well, in ground	2.00E-01	100	0	0	0	0	0	0	0	0	0
Water, river	1.02E-01	0	91	0	1	6	2	0	0	0	0
Water, salt, ocean	1.73E-01	0	99	0	0	1	0	0	0	0	0
Water, salt, sole	1.81E-04	0	11	0	5	76	7	0	0	0	0
Water, unspecified natural origin/kg	4.60E-01	100	0	0	0	0	0	0	0	0	0
Water, unspecified natural origin/m3	8.23E+00	0	99	0	0	0	1	0	0	0	0
Water, well, in ground	3.89E-03	0	7	0	12	70	10	0	0	0	0
Wood and wood waste, 9.5 MJ per kg	1.50E-04	0	45	0	22	0	2	9	2	8	12
Wood, hard, standing	1.77E-06	0	10	0	10	37	43	0	0	0	0
Wood, soft, standing	2.65E-05	0	78	0	3	7	12	0	0	0	0
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	3.69E-06	0	0	0	100	0	0	0	0	0	0

Table 5.10. Contribution by input parameter to use of raw materials for the manufacture of PRF resin (continued).

Substance			Process input chemicals					Transportation		PF process	
		PF resin process	Phenol	Resorcinol	Methanol	Ethanol	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
	MJ/kg resin	% contribution									
Electricity from other gases	5.92E-03	0	71	0	2	0	3	0	0	0	24
Electricity from other renewables	3.41E-02	0	71	0	2	0	3	0	0	0	24
Energy, from hydro power	1.01E-01	0	71	0	2	0	3	0	0	0	24
Energy, gross calorific value, in biomass	4.44E-02	0	99	0	0	1	0	0	0	0	0
Energy, kinetic (in wind), converted	7.10E-05	0	7	0	8	37	48	0	0	0	0
Energy, potential (in hydropower reservoir), converted	3.41E-02	0	96	0	1	3	1	0	0	0	0
Energy, solar, converted	1.22E-06	0	8	0	6	45	40	0	0	0	0

Table 5.11. Contribution by input parameter to air emissions for the manufacture of PRF resin.

Emissions to air	kg/kg resin	PF resin process	Process input chemicals					Transportation		PF process	
			Phenol	Resorcinol	Methanol	Ethanol	Sodium hydroxide	Diesel truck	Diesel rail	Natural gas	Electricity
		% contribution									
Aldehydes, unspecified	2.36E-05	0	19	0	2	0	0	62	15	1	1
Ammonia	1.66E-06	0	54	0	7	1	14	6	1	0	17
Benzene	5.13E-04	0	100	0	0	0	0	0	0	0	0
Carbon dioxide, biogenic	1.84E-03	0	91	0	3	2	1	1	0	1	1
Carbon dioxide, fossil	1.23E+00	0	76	0	5	1	1	5	1	6	6
Carbon monoxide	1.52E-03	0	25	0	23	0	0	35	5	10	2
Carbon monoxide, biogenic	1.79E-06	0	97	0	1	2	0	0	0	0	0
Carbon monoxide, fossil	8.34E-04	0	99	0	0	1	0	0	0	0	0
Cumene	7.42E-04	0	100	0	0	0	0	0	0	0	0
Dinitrogen monoxide	2.24E-06	0	69	0	3	1	4	0	0	0	23
Ethene	1.08E-05	0	19	0	0	81	0	0	0	0	0
Formaldehyde	8.83E-06	100	0	0	0	0	0	0	0	0	0
Hydrocarbons, aliphatic, alkanes, cyclic	1.46E-06	0	100	0	0	0	0	0	0	0	0
Hydrocarbons, aromatic	9.69E-06	0	98	0	0	2	0	0	0	0	0
Hydrogen	1.24E-05	0	82	0	0	1	17	0	0	0	0
Hydrogen chloride	2.98E-05	0	80	0	2	1	2	0	0	0	15
Hydrogen fluoride	3.05E-06	0	74	0	2	0	3	0	0	0	20
Lead	2.08E-08	0	55	0	24	2	2	2	0	1	15
Mercury	8.55E-09	0	69	0	3	1	4	1	0	0	21
Methane	1.58E-03	0	42	0	34	0	1	1	0	12	10
Methane, biogenic	9.94E-06	0	98	0	0	1	1	0	0	0	0
Methane, fossil	5.02E-03	0	97	0	2	1	0	0	0	0	0
Methanol	5.98E-05	9	0	0	91	0	0	0	0	0	0
Nickel	1.56E-06	0	97	0	1	0	0	0	0	0	1
Nitrogen oxides	3.70E-03	0	59	0	8	0	1	14	4	6	7
NMVOC, non-methane volatile organic compounds, unspecified origin	2.80E-03	0	50	0	27	0	0	8	3	10	2
Organic substances, unspecified	3.24E-04	0	10	0	0	0	0	88	1	0	0
Particulates	3.01E-06	100	0	0	0	0	0	0	0	0	0
Particulates, < 10 um	2.19E-04	0	36	0	2	0	1	33	20	2	6
Particulates, < 2.5 um	4.63E-05	0	98	0	1	1	0	0	0	0	0
Particulates, > 10 um	6.00E-05	0	97	0	0	2	0	0	0	0	0
Particulates, > 2.5 um, and < 10um	7.93E-05	0	98	0	0	1	0	0	0	0	0
Particulates, unspecified	2.78E-04	0	68	0	4	0	3	1	0	1	23
Phenol	4.17E-06	100	0	0	0	0	0	0	0	0	0
Propene	2.75E-04	0	100	0	0	0	0	0	0	0	0
Sulfur dioxide	1.42E-03	0	99	0	0	1	0	0	0	0	0
Sulfur oxides	7.49E-03	0	37	0	38	0	1	2	0	14	7
VOC, volatile organic compounds	3.38E-05	100	0	0	0	0	0	0	0	0	0
	MJ/kg resin										
Heat, waste	9.08E+00	0	93	0	6	1	1	0	0	0	0
	Bq/kg resin										
Noble gases, radioactive, unspecified	1.44E+02	0	12	0	7	40	41	0	0	0	0
Radioactive species, unspecified	4.98E+03	0	70	0	3	0	3	0	0	0	24
Radon-222	3.04E+02	0	13	0	6	44	37	0	0	0	0

5.8 Carbon Content and Footprint of PRF Resin

When it comes to climate change and related issues as a result of increased greenhouse gas emissions to the atmosphere, two topics are of interest: 1) the amount of carbon store in a material that can in some instances be considered as an offset when sequestered near-term to reduce the amount of CO_2 emissions to the atmosphere, and 2) the carbon footprint of a material that gives the amount of greenhouse gases released to the atmosphere during its life cycle. The sum of the two values with carbon store as a negative value gives the net CO_2 impact of a material upon the environment.

Cured PRF resin is comprised of 57% of carbon by weight for 0.57 kg/kg resin 100% solids. The carbon content is an estimate which can vary with changes in formulation and resin mix, and considers the use of paraformaldehyde hardener and no formaldehyde loss. Unfortunately this carbon cannot be considered as a carbon store offset to CO_2 emissions since it is not continuously renewing in the carbon cycle. The resin carbon was sequestered hundreds of million years ago during the formation of the fossil fuels that are used as its feedstock. The carbon in the resin is unlike the carbon stored in trees and wood which was sequestered near-term within the last 30-100 years, is part of a continuously renewing carbon cycle, and can be counted as an offset against emissions of CO_2 to the atmosphere when looking at a materials carbon footprint and impact upon global warming.

The carbon footprint is determined by the CO_2 equivalent of all greenhouse gas (GHG) emissions during the life cycle of a product; in this case from resources in the ground through extraction, deliveries and manufacturing of the liquid PRF resin. The CO_2 equivalent of each GHG can be determined by multiplying its comparative reactive factor in the atmosphere to that for carbon dioxide based on a 100 year time horizon (IPCC 2007). There are three GHGs that normally occur for the life cycle of wood products and resins—CO_2 (fossil fuel contributions), CH_4 (methane), and N_2O (listed as nitrous oxide and dinitrogen oxide for the LCI output), other GHGs include CFC which do not occur or are insignificant for this study. The total carbon footprint for the life cycle of PRF resin from cradle-to-gate is given by the following—the values of each contribution are given in Table 5.6:

$$\text{Carbon Footprint kg-}CO_2\text{ eq} = CO_2\text{ kg} + (CH_4\text{ kg x 25}) + (N_2O\text{ kg x 298})$$

The carbon footprint in kg-CO_2 equivalent (eq) is determined by the mass of each of its contributors times how reactive they are in comparison to CO_2 in the atmosphere, e.g., CH_4 (methane) is 25 times more reactive than CO_2 and N_2O (nitrous oxide) is 298 times more reactive than CO_2. Considering the total emissions from cradle-to-product gate for each of these contributors gives a total of 2.3225 kg-CO_2 eq. per kg of cured PRF resin, see Table 5.12. These emissions are generated in the process of extracting the fuel and feedstock, the energy equivalence of feedstock, generation of electricity, delivery of fuel and feedstock, and the combustion fuel in the manufacture of the resin.

Table 5.12. The carbon footprint given in kg-CO2 equivalent (eq) for 100% solids PRF resin.

Greenhouse gas (GHG)	GHG Contribution kg/kg resin 60% solids	CO_2 equiv. multiplier	Carbon Footprint kg-CO_2 eq/kg resin 100% solids
CO_2	1.23	1	2.0460
Methane (CH_4)	0.00661	25	0.2754
Nitrous oxide (N_2O)	0.00000224	298	0.0011
Total			2.3225

5.9 Study Discussion

The data documented in this chapter on the manufacture of PRF resin forms a foundation for the scientific assessment of its environmental performance. The PRF resin data should not be considered as a stand alone product; rather it should be used when conducting life-cycle inventories and assessments of wood composite products that use this resin as a bonding agent during their manufacture. Resins are an integral component and contributor to the performance of wood composites. A life-cycle assessment of the use of resins in composites can be used in a number of ways to show their favorable performance for such environmental issues as sustainability, global warming, climate change, carbon footprint, carbon storage, carbon trading and caps, carbon taxes, green purchasing, and green building. The data can be used as stated or in a life-cycle assessment to compare wood composite products to various competitive materials or assemblies of various materials. Individual LCI data of PRF resin can be used as a benchmark for process or product improvements or for comparing performance to those of other materials but it is important to make comparisons on an equal product performance basis since resin efficiency varies by resin type. The LCI data for PRF resin is on a 60% solids basis, the concentration of the resin as typically used, for LCI data on a 100% solids basis, divide LCI data by 0.6.

5.10 Conclusion

A cradle-to-product gate life-cycle inventory (LCI) study was conducted of manufacturing 1.0 kg of phenol-resorcinol-formaldehyde (PRF) resin at 60% solids—the LCI functional unit for this study—in the U.S. The study covered data analyses from the raw resources in the ground through resin manufacturing for the production year 2005. Production data was collected by survey of resin manufacturers representing 63% of total U.S. production of PRF resin for the glue laminated beam and I-joist industries that annually used about 15.5 million kg of PRF resin at 60% solids. PRF production is small in comparison to that for PF resin; it is only a little over 1% of annual production. Secondary LCI data from the Franklin Associates Limited and Ecoinvent databases were used for input chemicals, fuels, electricity and transportation. Ecoinvent data was adjusted to U.S. fuels, electricity, and transportation values.

The quality of the LCI data collected for the manufacture of PRF resin was high as judged by assessments for similarity of values, molar ratio of formaldehyde to phenol plus resorcinol, and the mass flow of material in and out of the process. Any data questions were resolved by re-contacting the manufacturers that participated in the survey. The molar ratio of formaldehyde to phenol plus resorcinol was found to be 0.61 which is as expected less than 1.0 for a contemporary industrial resin.

Assigning of environmental burden in the production of PRF resin was entirely to the product since no co-products were produced during the process. For the output functional unit of 1.0 kg of PRF resin at 60% solids, the main input components were phenol of 0.277 kg, resorcinol at 0.190 kg, and methanol at 0.103 kg, and water at 0.656 kg for resin and processing use. Small amounts of ethanol and sodium hydroxide were also used. Methanol is used in a reactor to produce formaldehyde which is then used with the addition of some sodium hydroxide in a second reactor to produce the PRF resin. Additional water to make the resin occurs during the condensation polymerization in the reactor.

Environmental impacts were assessed for those at the resin manufacturing site (referred to as on-site emissions) and those for cradle-to-product gate which begins with resources in the ground through extraction, generation, delivery, and resin manufacture. On-site impacts are generally smaller compared to the cradle-to-product gate impacts with the exception of VOC, formaldehyde and phenol emissions that are generated on-site. Per 1.0 kg of liquid resin the on-site energy use of 1.58 MJ compared to 40.45 MJ/kg neat resin for cradle-to-product gate, and emissions to air such as CO_2, CO, VOC, particulate, formaldehyde, methanol, and phenol are 6%, 6%, 100% (cradle-to-gate input LCI values only consider individual VOC contributors and do not give them as a VOC grouping), 1%, 100%, 9% and 100% of the cradle-to-gate values. The on-site emissions to water were also smaller. Even water use was much less at only 1% of cradle-to-product gate values. Overall the resin manufacturing operations are resource efficient and relatively friendly to the environment.

In terms of energy equivalent for fuels and feedstock from cradle-to-gate, the manufacture of phenol and methanol from in-ground fuel resources contributed to 77.9%, and 11.3% respectively, whereas the contribution of sodium hydroxide (0.4%) and ethanol (0.8%) to the total energy were insignificant. No LCI data was available in the SimaPro databases such as Franklin or Ecoinvent to trace its manufacture back to in-ground resources; as such it was not included in the analysis other than to state its use as a resource. The contribution of the transportation of chemical inputs (2.85%) to the resin plants, and on-site processing fuels and electricity (6.77%) were minor to the total energy.

A sensitivity of the input parameters to the output use of materials and emissions to air, water, and land were likewise dominated by input phenol and methanol chemicals. Other inputs of on-site fuel and electricity use, and transportation of chemicals to the plant, all were minor contributors. Changing the input value of phenol and/or methanol would result in expected proportional outputs of emissions; changes in other minor parameters generally would not result in significant changes in output.

The carbon footprint from cradle-to-gate to produce PRF resin is 2.3225 kg-CO_2 eq per 1.0 kg of 100% solids resin. The carbon footprint accounts for all greenhouse gas emissions during the life cycle of a product, in this case from cradle-to-gate. Although PRF cured resin has a carbon component of 57%, it is not considered as an offset for CO_2 emissions to the atmosphere during processing since its carbon was not sequestered near-term and it is not a continuously renewing carbon cycle.

To benefit from the availability of the LCI database for PRF resin, the following additional studies are recommended: 1) extract pertinent data that documents the favorable environmental performance of PRF resin and 2) edit prior CORRIM LCI studies that used PRF resin to include the LCI data developed in this study.

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Appendix 1: Resin Manufacturing Survey Form

CORRIM Survey

The Consortium for Research on Renewable Industrial Materials (CORRIM)

<u>Urea-Formaldehyde</u> Resin Production Data

The information from this survey will be used in a project by CORRIM, a consortia comprised of universities, industry, and government groups. CORRIM is developing a life-cycle database and conducting assessments to document the favorable environmental performance of wood building materials. As part of this study we need to collect production data on the resins used to produce wood-based composite building products such as plywood, oriented strand board, laminated veneer lumber, I-joists, particleboard and medium density fiberboard. The resin database will be used within the databases of each wood-based composite product as the basis for the scientific evaluation of environmental performance and energy requirements of building materials through their life cycles. It is hoped that the output of the study will be used to competitively position wood in the marketplace over non-wood types of building materials.

This CORRIM survey is designed specifically for resin production facilities; resins that we are collecting data for include: urea formaldehyde, phenol formaldehyde (both liquid and powder), melamine urea formaldehyde, phenol resorcinol formaldehyde, and polymeric isocyanate. Questions will be concentrated on annual production (but responses can also be for a batch of a given weight or per pound of resin), electricity and fuel usage, chemicals usage, and environmental emissions. We realize that you may not have all the information requested. The data you are able to provide will be greatly appreciated. Our intent is to maintain strict confidentiality of data and its source; only weight-averaged data of the industry will be used in the database.

Company: ______________________________

Facility Sites (city, state—
list all included): ______________________________

Should we have a follow-up question about the data, please provide the name and the following information for the contact in your company.

Name: ____________________ Title: ____________________

Telephone: ____________________ E-mail: ____________________

If you have questions about the survey, contact:
Jim Wilson
CORRIM, Inc.
2624 NW Lupine Place
Corvallis, OR 97330
541-829-1622
jim.wilson@oregonstate.edu

Resin Production Please provide units of measurement if different than stated. Ideally we would like to collect data on a per unit of production basis, i.e., lbs of urea per lbs of UF resin produced at 100% solids, but will accept any production unit, i.e., lbs. of urea used to produce lbs. of UF resin annually or lbs. of chemical to produce a lb. of UF at 100% solids. The important factor here is that the units of production are stated, we can make the unit conversions if necessary.

	Production size of U.S. resin industry		**Survey Response**
1.	Estimated annual U.S. production of urea-formaldehyde resin for wood composite panel industry—all U.S. manufacturers.	lbs., tons, etc. and state whether 100% solids weight	______________
2.	Give production year	2005?	______________

	Production data to UF resin		**Survey Response**
1.	Total urea-formaldehyde produced by your company annually	lbs., tons, etc. and state whether 100% solids weight	______________
2.	Give production year	2005?	______________
3.	Number of plant sites represented in your survey data	1, 2, 3, …?	______________
4.	Urea input to process to make UF resin	lbs., tons, etc. (give basis i.e. lb/year, lb/ UF resin, lb/ton UF	______________
5.	Formaldehyde input to process to make UF resin	lbs., tons, etc (give basis i.e. lb/year, lb/ UF resin, lb/ton UF	
6.	Methanol input to process to make UF resin	lbs., tons, etc (give basis i.e. lb/year, lb/ UF resin, lb/ton UF	______________
7.	Other chemicals input to process (list below)	lbs., tons, etc (give basis i.e. lb/year, lb/ UF resin, lb/ton UF	______________

Water use for UF production	Give basis i.e. gal/year, gal/ lb. UF resin, gal/ton UF resin	Survey Response
1. For producing UF resin		
2. For cooling tower		
Other uses, please state		
Total water use		

Water use (check source)

Municipal water source

Well water source

Recycled water

Transportation method and distance to deliver

Deliver urea (one-way distance)	Miles	% of Total
Truck		
Rail		
Ship		
Other		
		Total= 100%

Average distance of delivery for urea	Miles	

Deliver formaldehyde (one-way distance) Miles | % of Total

Truck ____________

Rail ____________

Ship ____________

Other ____________

Total= 100%

Average distance to deliver resin to mill Miles ____________

Deliver methanol (one-way distance) Miles | % of Total

Truck ____________

Rail ____________

Ship ____________

Other ____________

Total= 100%

Average distance to deliver resin to mill Miles ____________

Transportation method and distance to deliver other input materials; please list other materials here:

Deliver other input materials (list material) Miles | % of Total

Truck ____________

Rail ____________

Other ____________

Total= 100%

Average distance to deliver other Miles ____________

Energy Consumption to Produce UF resin (Please provide units of measurement if different.)

1.	Electricity	kWh (give basis annual or per lb UF resin)	________________
2.	Steam	lbs. (at temperature °F?)	________________
3.	If you know fuel source used to generate the steam, please state type, i.e. natural gas, hog fuel		________________
4.	Fuel use		________________
	Wood waste	Tons	________________
	Residual fuel oil	42 gal. bbls. or gal.	________________
	Distillate fuel oil	42 gal. bbls. or gal.	________________
	Liquid propane gas	Gallons	________________
	Natural gas	$ft.^3$	________________
	Gasoline and kerosene	Gallons	________________
	Diesel	Gallons	________________
	Other (Specify)		
	Less energy sold or transferred		
	a. Electricity	kWh	________________
	b. Steam	lbs. (at temperature °F?)	

Note: please list fuel (i.e., propane, diesel, etc.) consumption in appropriate category above for use of fork lifts.

14. If you have a boiler, what is its heat source? Mark appropriate fuel sources, i.e., X

_______Natural gas

_______Propane

_______Oil

_______Other (please list)

Emissions Control Devices and plant Emissions

The following is a chart of emission control devices and a listing of chemical compounds that are observed and/or permitted. Please fill in all information related to the control devices. Then list all compounds that are collected and known for the mill from all control device sources. If you recently applied for an air permit, use those numbers. Fill in all that apply and for which you have data. If you don't have an emissions control device, skip to next page and simply state as such, cross out ECD1 and give the plant emissions for the production of UF resin. Make sure to state unit (lbs, tons, annual UF production) of resin that the emissions are based on.

	ECD 1	**ECD 2**	**ECD 3**
Equipment type controlled (boiler, reactor, etc.)			
Type of device (i.e., RTO, RCO, Scrubber, WESP, etc.)			
Manufacturer and year installed			
ECD exhaust temperature (^{o}F) and flow rate (acfm)—if known			
Electricity use in % of total plant or kWh, please state units per unit of UF produced			
Natural gas use in % of total mill use, Dtherms, or ft.^{3}, please state units per unit of UF produced			

Organic Compound	ECD 1	ECD 2	ECD 3
Equipment type controlled (boiler, reactor, etc.)			
	lbs or tons/unit of UF produced	lbs or tons/unit of UF produced	lbs or tons/unit of UF produced
Unit of emission			
CO_2 (you probably don't have, but we can calculate from fuel use)			
CO			
NO_X			
SO_2			
VOC			
Particulate			
PM10			
Acrolien*			
Acetaldehyde*			
Propionaldehyde*			
Formaldehyde*			
Methanol*			
Phenol*			
Water Vapor			
HAPS; you may want to provide total HAPS rather than specific chemicals*			
Other (please specify)			

Solid Emissions From All Known Sources (please provide units of measurement)

Emission	Quantity (i.e., lbs., tons)	Method of disposal or end use (i.e., land fill, landscaping, sewer)
Water (BOD, COD, suspended solids, etc.)		
Other (please specify)		