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A Cradle-to-Gate Life Cycle Assessment of North American Wood Product Resin Systems

Prepared for: U.S. Endowment for Forestry and Communities and
USDA Forest Service Forest Products Laboratory

Prepared by: The Athena Sustainable Materials Institute

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On behalf of Athena Institute

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General Summary

The U.S. Endowment for Forestry and Communities and the USDA Forest Service Forest Products Laboratory commissioned the Athena Sustainable Materials Institute to update four previous cradle-to-gate life cycle assessments (LCAs) of wood product resin systems (urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), and phenol-resorcinol-formaldehyde (PRF) as developed by Wilson 2009 [1] and develop new cradle-to-gate LCAs for melamine-formaldehyde (MF), emulsion polymer isocyanate (EPI) and polymer emulsion polyurethane (PEP) wood resins.

This LCA project has been conducted in accordance with ISO 14040:2006 [2], ISO 14044:2006 [3] and ISO 21930:2017 [4] and thus aligns with the most recent version of the Underwriters Laboratories Environment (ULE) Product Category Rules (PCR) for Building-Related Products and Services, Part A: Life Cycle Assessment Calculation Rules and Report Requirements [5] and Part B, North American Structural and Architectural Wood Products, Environmental Product Declaration (EPD) Requirements [6].

The study draws on confidential resin industry life cycle inventory (LCI) surveys completed for the reference year 2019. For each precursor or resin system, a minimum of three (3) and a maximum of six (6) surveys were confidentially completed by nine (9) industry participating facilities.

A number of participating facilities manufacture both formaldehyde, and related resins and, where necessary, a parametrized mass allocation (PMA) approach was also developed and applied to better partition (separate) the LCI data for the production of formaldehyde (precursor) from resin production data based on updated 2019 industry process data for two formaldehyde production technologies employed by industry (Silver catalyst and Formox processes) [1]. The study also draws on updated 2020 North American upstream methanol data – the key input in formaldehyde production [1]. The LCA results were benchmarked against Wilson 2009's previous study [1] as well as scientific literature and updated ecoinvent v3.7.1 2021 LCI datasets as a quality check. For the two-part EPI and PEP adhesives, Athena developed a generic plant model combining the manufacture of both "base" and "cross-linker" polymers for the two adhesives of interest.

All resin data is presented on a 100% solids basis. To determine the data for a resin at its stated use solids percentage (e.g., UF resin at 65% solids), multiply the 100% solids data in this report by the decimal value of its stated solids use (e.g., 0.65).

This report includes publicly available Annexes (A, B, and C) to document the data benchmarks with Wilson 2009 [1], ecoinvent v3.7.1 2021 LCI datasets and scientific literature, background LCI datasets used to model chemical input precursors and final resins, and sensitivity check results. A Supplementary Excel Annex is developed and presents the SimaPro LCI results for each resin on a system process basis as well as the LCA results per ISO 21930:2017 [4]. These supplementary LCA results are intended to be used by LCA practitioners in North America to develop ISO conforming wood product LCAs and EPDs.

Terms and Definitions

ISO 14040:2006/Amd1:2020 and ISO 14044:2006/Amd1:2017/Amd2:2020 [2], [3] – Clause 3 Terms and Definition.

Allocation: Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Comparative assertion: Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function.

Life cycle: Consecutive and interlinked stages, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Impact Assessment (LCIA): Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation: Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Life Cycle Inventory (LCI): Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Product system: Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

System boundary: Boundary based on a set of criteria specifying which unit processes are part of the system under study

Sensitivity check: Process to determine whether the information obtained from a sensitivity analysis is relevant for reaching the conclusions and for giving recommendations

Uncertainty analysis: Systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability.
Note: Either ranges or probability distributions are used to determine the uncertainty in the results.

ISO 21930:2017 [4] - Clause 3 Terms and definitions

Average data: Data based on a fully representative sample for a construction product or construction service, provided by one or more suppliers, either from their multiple plants or based on multiple similar construction products of the supplier(s).

Co-product: Any of one or more products from the same unit process, but which is not the object of the assessment.

Declared unit: Quantity of a construction product for use as a reference unit in an EPD based on LCA for the expression of environmental information in information modules.

Information module: Compilation of data to be used as a basis for an EPD, covering a unit process or a combination of unit processes that are part of the life cycle of a product.

Product category: Group of construction products that can fulfill equivalent functions.

ISO 14025:2006 [7] - Clause 3 Terms and definitions

Type III Environmental Product Declaration (EPD): Providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information
Note 1 the predetermined parameters are based on the ISO 14040 series of standards.
Note 2 the additional environmental information may be quantitative or qualitative.

Product Category Rules (PCR): Set of specific rules, requirements, and guidelines for developing Type III environmental declarations for one or more product categories.

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Acronyms and Abbreviations

ADP_f	Abiotic depletion potential for fossil resources
AP	Acidification potential
Athena	The Athena Sustainable Materials Institute
BOD	Biological oxygen demand
CFC-11	Trichlorofluoromethane
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CRU	Components for re-use
D	Direct (the source of data)
DOC	Dissolved organic carbon
E	Estimated (the source of data)
EE	Recovered energy exported from the product system
Endowment	U.S. Endowment for Forestry and Communities, Inc.
EP	Eutrophication potential
EPD	Environmental product declaration
EPI	Emulsion polymer isocyanate
FFD	Fossil fuel depletion
FPL	USDA Forest Service Forest Products Laboratory
FW	Consumption of fresh water
GHG	Greenhouse gas
GWP 100	Global warming potential, 100 years’ time horizon
HAP	Hazardous air pollutant
HLRW	High-level radioactive waste, conditioned, to final repository
HWD	Hazardous waste disposed
I	Indirect (the source of data)
ILLRW	Intermediate- and low-level radioactive waste, conditioned, to final repository
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometer
kWh	kilowatt hours
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value
MER	Materials for energy recovery
MF	Melamine–formaldehyde
MJ	Mega joule
MR	Materials for recycling
MUF	Melamine–urea–formaldehyde

N	Nitrogen
NCV	Net caloric value
NHWD	Non-hazardous waste disposed
NMVOC	Non-methane volatile organic compounds
$NRPR_M$	Non-renewable primary energy carrier used as material
$NRPR_E$	Non-renewable primary energy carrier used as energy
NRSF	Non-renewable secondary fuel
O_3	Ozone
ODP	Ozone depletion potential
PCR	Product category rules
PEP	Polymer emulsion polyurethane
PF	Phenol–formaldehyde
PGF	Plant generic formulation
PM-FIL	Filterable particulate matter less than or equal to 30microns in diameter
PM10-FIL	Filterable particulate matter less than or equal to 10microns in diameter
PM25-FIL	Filterable particulate matter less than or equal to 2.5microns in diameter
PMA	Parametrized mass allocation approach
PRF	Phenol–resorcinol–formaldehyde
RE	Recovered energy,
RF	Reference year
RPR_M	Renewable primary energy carrier used as material
RPR_E	Renewable primary energy carrier used as energy
RSF	Renewable secondary fuel
SFP	Smog formation potential
SM	Secondary material
SO_2	Sulfur dioxide
TOC	Total suspended solids
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UF	Urea–formaldehyde
ULE	Underwriters Laboratories Environment
U.S. EPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds

1 Introduction

The U.S. Endowment for Forestry and Communities and the USDA Forest Service Forest Products Laboratory commissioned the Athena Sustainable Materials Institute to update the previous cradle-to-gate life cycle assessment (LCA) study of wood resins (urea–formaldehyde (UF), melamine–urea–formaldehyde (MUF), phenol–formaldehyde (PF), and phenol–resorcinol–formaldehyde (PRF) as developed by Wilson 2009 [1] and develop new cradle-to-gate LCAs for melamine–formaldehyde (MF), emulsion polymer isocyanate (EPI) and polymer emulsion polyurethane (PEP) wood resins.

Life cycle assessment is an analytical technique used to comprehensively quantify and interpret the energy and material flows to and from the environment over the entire life cycle of a product, process, or service [2], [3]. Environmental flows include emissions to air, water, land, and the consumption of energy and material resources. By including the potential impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product.

This LCA study has been conducted in accordance with the ISO 14040:2006 [2], ISO 14044:2006 [3] and ISO 21930:2017 [4], and therefore, the LCA results are deemed suitable to be used in the framework of the wood product EPDs as per the ULE Product Category Rules (PCR) for Building-Related Products and Services, Part A Life Cycle Assessment Calculation Rules and Report Requirements [5] and Part B North American Structural and Architectural Wood Products, EPD Requirements [6].

Sections 2 and 3 of the LCA report describe the study goals and scope, including the key primary and secondary data supporting the LCA model and results. Sections 4 through 10 are dedicated to describing the LCI flows associated with the key precursor (formaldehyde) and UF, MUF, MF, PF, PRF, EPI and PEP wood resins, respectively. Section 11 presents the LCA results as per ISO 21930:2017 [4]. Section 12 brings together the findings from the inventory analysis and the impact assessment to identify significant issues in the context of the goal and scope of the study. Issues are identified via contribution and dominance analysis for the wood resins. This section then provides an evaluation of the study's completeness and consistency in relation to the goal and scope of the study. To assess how factors such as allocation methods and uncertainties in data would affect the reliability of the results and conclusions, sensitivity and Monte Carlo uncertainty analyses were conducted. Finally, Section 12 presents the LCA study's conclusions, limitations, and recommendations.

2 Goals of the Study

This is a project commissioned by the Endowment and FPL to conduct a LCA study of seven (7) wood resins for U.S. region in accordance with the ISO 14040:2006 [2], ISO 14044:2006 [3] and ISO 21930:2017 [4], to support the development of Environmental Product Declarations (EPDs) for North American wood products according to ULE Part A PCR [5] and ULE Part B PCR [6].

The primary intent of the LCA study is to make the wood resins LCA results available to wood product LCA practitioners such that they consistently model the resin input used in the manufacture of composite wood products. Furthermore, the intended audience for these LCA results includes architectural, engineering, and specifying professionals, LCA tool developers, academia, governmental organizations, policymakers, and other interested value chain parties who require reliable information on wood resins.

Cradle-to-gate LCA results based on this project report are not “comparative assertions”. This LCA report was externally reviewed by Maureen Puettmann, PhD, in accordance with ISO 14040/44 [2], [3] and ISO 21930:2017 [4].

3 Scope of the Study

The scope of the study entailed developing “cradle-to-gate” life cycle assessment for five formaldehyde-based wood resins – urea–formaldehyde (UF), melamine–urea–formaldehyde (MUF), melamine–formaldehyde (MF), phenol–formaldehyde (PF), and phenol–resorcinol–formaldehyde (PRF). In the framework of this project, formaldehyde production was also modeled as a unique unit process for each of these resins. New cradle-to-gate LCAs for emulsion polymer isocyanate (EPI) and polymer emulsion polyurethane (PEP) adhesives were also developed. Wilson 2009 [1] presents cradle-to-gate LCAs for four of the resins of interest – UF, MUF, PF and PRF – based on 2005 industry data, which proved to be a valuable resource for benchmarking purposes. This study draws on 2019 industry data as collected across nine (9) U.S. industry participating facilities producing the resins of interest and precursors used in their production (e.g., formaldehyde). These primary data are proprietary and therefore remain strictly confidential. The LCI modelling and results reporting have been sequenced and aggregated to maintain data confidentiality.

3.1 Declared Unit

The declared unit for this cradle-to-gate LCA study is defined as 1,000 kg (1 metric tonne) of each precursor or resin of interest on a 100% solids basis. To determine the data for a resin at its stated use solids percentage (e.g., UF resin at 65% solids), multiply the 100% solids data in this report by the decimal value of its stated solids use (e.g., 0.65).

3.2 System Boundary

For this study, the boundary is “cradle-to-gate”, which is limited to the Production stage (information modules A1 to A3 as depicted in Figure 1). Construction, Use, End-of-Life stages and optional supplementary module D- are excluded from the system boundary (see Figure 1).

Figures 2 and 3 present the Production stage system boundary for the declared wood resins manufacturing. Per ISO 21930, 7.1.7.2.1 [4], the system boundary with nature (natural environment) includes those technical processes that provide the material and energy inputs into the system and the subsequent manufacturing and transport processes up to the factory gate, as well as the processing of any waste arising from those processes.

Per ISO 21930, 7.1.7.1 [4], individual indicators for information modules A1, A2 and A3 are aggregated to a total for each indicator in the production stage.

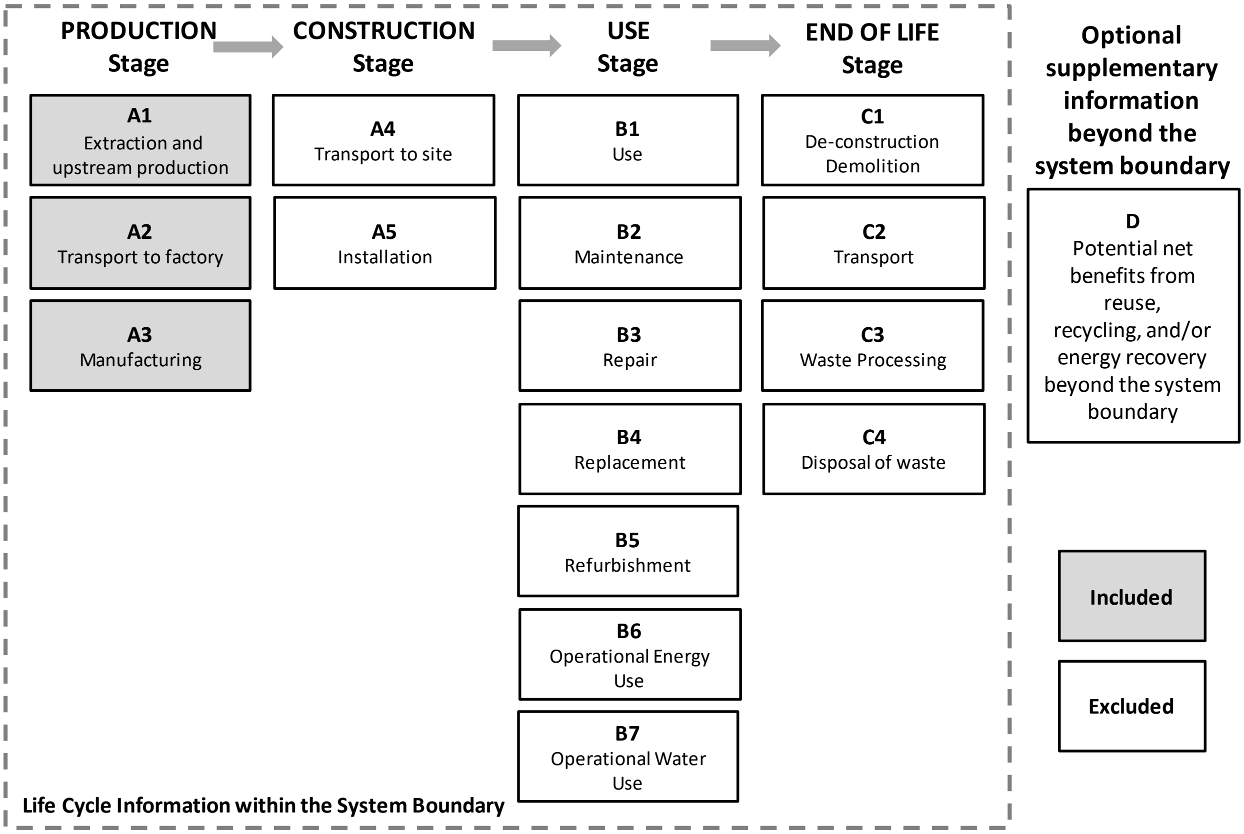

Figure 1 Common four life cycle stages and their information modules for construction products and the optional supplementary module [4]

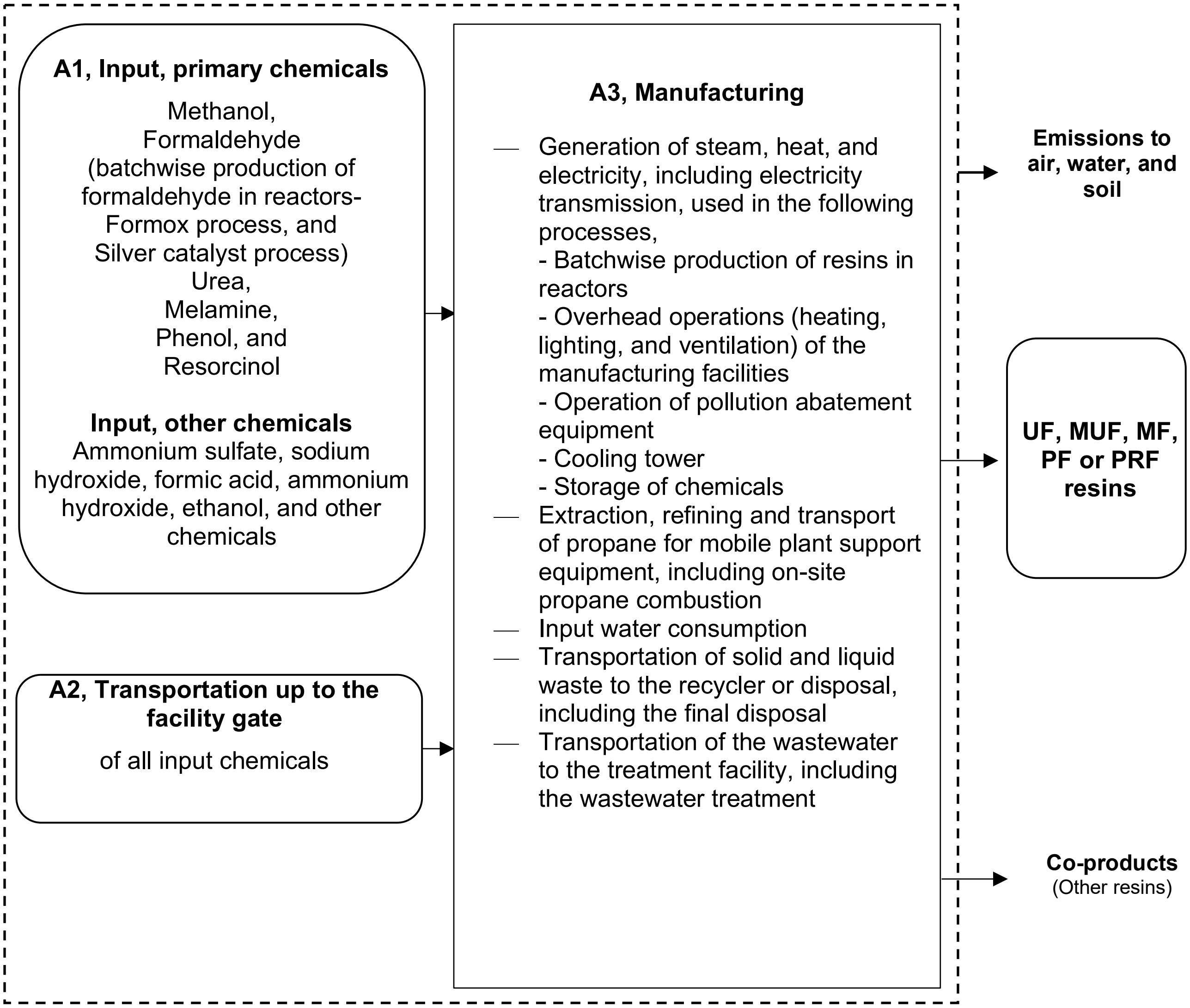

Figure 2 Production stage (module A1 to A3) system boundary of amino and phenolic wood resins manufacturing

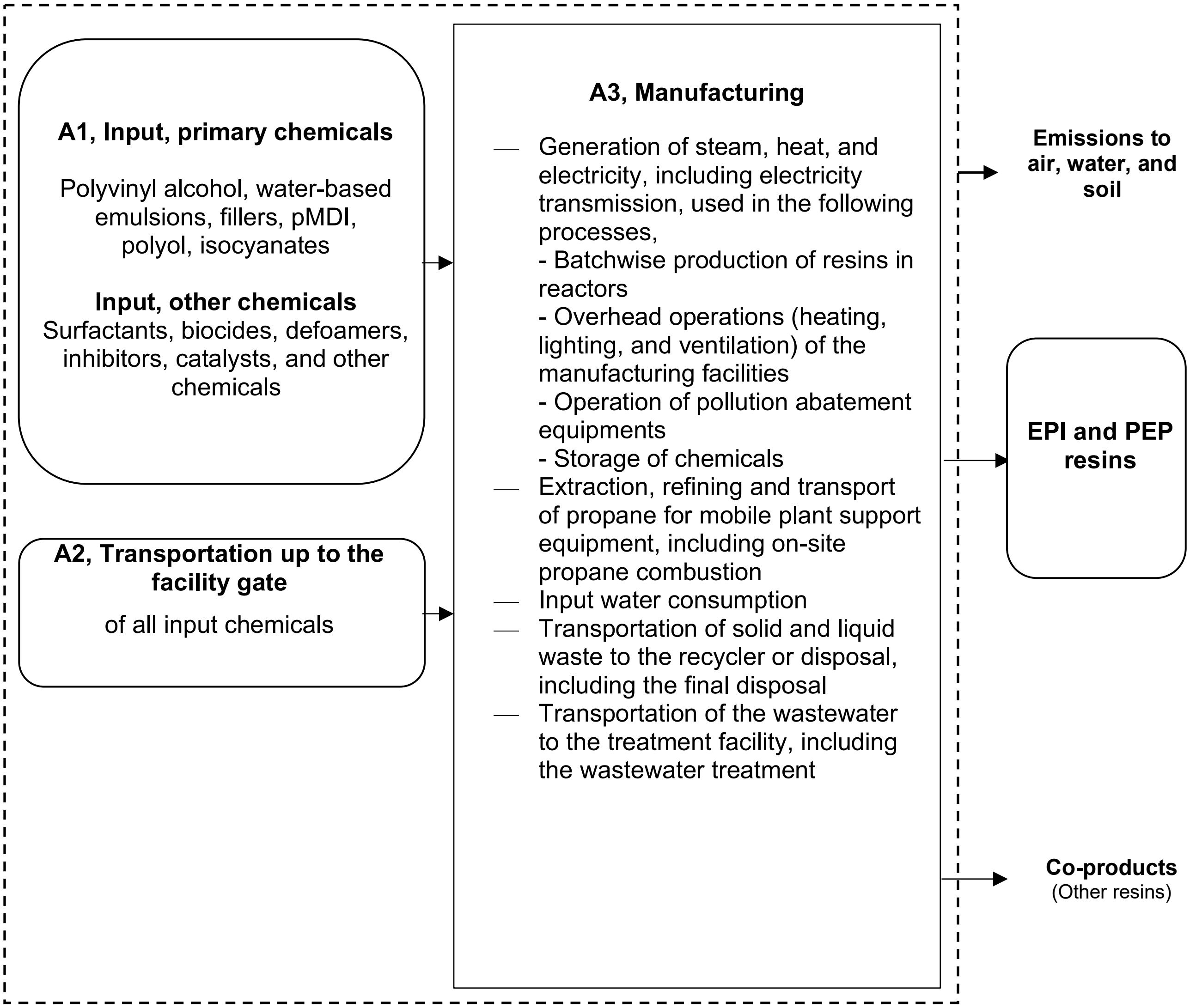

Figure 3 Production stage (module A1 to A3) system boundary of EPI and PEP resins manufacturing

Per ISO 21930, Section 7.1.7.2 [4], the Production Stage includes the following processes:

A1, Extraction and upstream production

This information module includes:

- A1, cradle-to-gate production of *formaldehyde* (precursor) used for the production of the five (5) amino (UF, MUF, and MF) and phenolic wood resins (PF and PRF)- see Tables 6 and 7;
- A1, cradle-to-gate production of the primary *chemicals* used in the manufacturing of all seven (7) wood resins (UF, MUF, MF, PF, PRF, EPI and PEP);
- A1, cradle-to-gate production of *additives* (e.g., surfactant, biocide, defoamer, filler, catalyst, defoamer, inhibitor, and other chemicals).

Cradle-to-gate production data include raw materials extraction and processing, transportation, generation of steam, heat, and electricity, including electricity transmission; extraction, refining and transport of fuel supply, including fuel combustion; water consumption, emissions to air, water and land, and waste management including transport up to the disposal.

A2, Transport to factory

This information module includes transportation data of all primary *chemicals* and *additives* from the upstream chemicals manufacturer to the resins manufacturing facilities (inbound transportation), including empty backhauls.

A3, Manufacturing

This information module includes:

- A3, generation of steam, heat, and electricity, used in manufacturing, including electricity transmission;
- A3, extraction, refining and transport of fuel supply (propane) for mobile plant support equipment, including on-site fuel combustion;
- A3, water consumption;
- A3, manufacturing of wood resins;
- A3, transportation of solid and liquid waste to the recycler or disposal (outbound transportation), including the final disposal; and
- A3, transportation of the wastewater to the treatment facility (outbound transportation), including the wastewater treatment.

No secondary materials (renewable and non-renewable) are used in the wood resins manufacturing processes. No energy recovered from secondary fuels and/or waste combustion is used in the manufacture of wood resins.

3.3 Cut-off Criteria

The cut-off criteria as per ISO 21930, 7.1.8 [4] were followed for this LCA study. Per ISO 21930, 7.1.8 [4], all input/output data collected were included in the LCI modelling developed using SimaPro v.9.2.0.2 2021 [10]. The cut-off rules are not applied to hazardous and toxic material flows – all of which are included in the life cycle inventory. No material or energy input or output was knowingly excluded from the system boundary. Any plant-specific data gaps for the reference year (RY) 2019 were filled with generic industry data from Wilson 2009 [1], such as the propane used for mobile plant support equipment. Process-specific carbon monoxide (CO) factor for formaldehyde production is calculated based on the technology mix of 65% Formox and 35% Silver processes (reference year 2019) and ecoinvent CO factors for formaldehyde production (in kg/kg)- see Table 39.4 [11].

This LCA study excludes the following processes:

- Shipping and packaging materials;
  Quantitative data for shipping and packaging were not available from facilities. This study assumes that wood resins are transported in railroad tank cars (tank wagons) and/or tank trucks [8], [9].
- Catalysts;
  Quantitative data for catalyst were not available from participating facilities. According to Wilson 2009, "*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*" [1].
- Capital goods and infrastructure;
- Human activity and personnel related activity (travel, furniture, office operations and supplies);
- Energy and water use related to company management and sales activities located either within the factory site or at another location.

3.4 LCA Software

The LCA model was developed using SimaPro v.9.2.0.2 2021 (https://simapro.com/) [10]. SimaPro LCA software contains recognized databases (e.g., U.S. LCI Database, 2015 and ecoinvent v3.7.1, 2021 database, Allocation, Cut-off by classification) that provide LCI datasets for upstream, core, and downstream material and processes. SimaPro 9.2.0.2 2021 also contains the U.S. EPA TRACI 2.1 2012 LCIA methodology, CML-baseline version 4.7 2016 LCIA methodology, and the Cumulative Energy Demand, LHV (NCV) version 1.0 November 2018 which are used for this LCA study (see Tables 2 and 3 for details).

3.5 Data Collection, Representativeness, Sources, and Calculations

Primary gate-to-gate LCI manufacturing and input transportation data were collected for precursor and resin production for the reference year 2019. A total of nine (9) U.S. resin facilities participated in this LCA study. LCI data (including the meta-data) were collected from a minimum of three (3) to up to six (6) U.S. resin facilities for each wood resin or precursor.

The LCA team identified a representative sample of resin plants based on technical attributes (purchased formaldehyde, on-site formaldehyde-Formox process, and on-site formaldehyde-Silver catalyst process), production scale (a mix of small, medium and large operations) and geographic location (a blend of Eastern, Western and Central facilities) to arrive at a representative sample of resin and adhesive manufacturing plants.

LCI data collection was based on customized LCI surveys for formaldehyde and the resins of interest. The LCI survey covered the following primary data for each facility for the 2019 reference year:

- Total manufactured products, and co-products;
- Main unit processes;
- Excluded processes;
- Pollution abatement equipment;
- Raw materials;
- Ancillary materials;
- Packaging materials;
- Electricity and fuel consumption;
- Water consumption (fresh and recycled);
- Inbound transportation distances and modes for all inputs;
- Emissions to air and water;
- Solid waste;
- Wastewater and other liquid waste;
- Waste outputs and their respective outbound transportation distances and modes.

The source of data is specified as (see Sections 4 to 10):

Direct (D)	based on measurements or purchasing/selling records of the surveyed facilities;
Indirect (I)	based on calculations made by the personnel of the surveyed facilities;
Estimated (E)	based on the industry average data and/or expert judgment.

All facility specific LCI data were weighted based on total annual production per unit mass of resin to calculate the weighted average LCI profile for each type of wood resin (100% solids) - see Table 1. The input/output LCI data (including meta-data) were verified and benchmarked with Wilson 2009 [1] and ecoinvent v3.7.1 [11] and/or other scientific literature for each product system by the Athena Institute - see Annex A, Tables A.1 to A.8.2. The quality of the LCI surveyed data was found to be “high” based on the expected molar ratio of formaldehyde to urea, melamine, phenol, resorcinol, or some combination of these chemicals (see Annex A, Table A.1) and mass balance (see Annex A, Table A.2). “Batchwise” production was the only method used by all surveyed plants. No plant reported the “continuous” production method for any of the declared wood resins or formaldehyde. Plant specific generic formulation data were collected for each wood resin and formaldehyde for the reference year 2019. There is no biogenic content in the declared wood resins or precursor. Purchased electricity and natural gas were reported to be the primary manufacturing energy inputs. Water use within the facilities consists of formulation water for resin production and water used for cooling and boiler make-up. All resin facilities operate either a dry or wet cooling tower. Resins facilities typically use fabric filters - high temperature (baghouses) as pollution abatement equipment. Quantitative primary data for shipping and packaging were not available. This LCA study assumes that wood resins are transported in railroad tank cars and/or tank trucks [8], [9].

Table 1 Simplified example of the weighted average approach for inputs and outputs data

Product type	**UF resin**	
No. of resin facilities	5	
Reference year	2019	
Declared unit	1,000 kg	
Selected Parameter	Total annual production of UF resin (100% solids) per facility (in metric tonne)	
Facility No.	Example: Production (in metric tonne)	Example: Weighted average factor (in %)
Facility 1	1,000	20%
Facility 2	1,000	20%
Facility 3	1,000	20%
Facility 4	1,000	20%
Facility 5	1,000	20%
Total	**5,000**	**100%**

The transportation modes and tonne*kilometers (tkm) for all inputs and waste outputs per each wood resin and formaldehyde are reported in Sections 4 to 10. Transportation data (in tkm) are calculated per input flow and waste output based on primary data. All calculated transportation data per input flow and waste output (in tkm) are then summed up to the total values (in tkm) per transportation mode. Transportation activities are included consistently in the respective life cycle modules. Trucking and rail are the primary transportation modes for all inputs.

This LCA study draws on appropriate LCI datasets provided by (see Sections 4 to 10 and Annex B, Tables B.1 to B.3):

- Primary data gathered from resin manufacturers (confidential).

- North American and global LCI databases such as the U.S. LCI Database, 2015 (http://www.nrel.gov/lci/), and ecoinvent 3.7.1 2021, allocation, cut-off database (http://www.ecoinvent.org/). Both are included in the LCA software SimaPro v.9.2.0.2 2021 [10].

Data calculation procedures follow ISO 14044 [3] and ISO 21930 [4]. The same calculation procedures are applied throughout this LCA study. Per ISO 21930, 7.2.2 [4], when transforming the inputs and outputs of combustible material into inputs and outputs of energy, the net calorific value (lower heating value) of fuels is applied according to scientifically based and accepted values specific to the combustible material. SI units are used for the LCA data and results.

3.6 Data Quality Requirements and Assessments

Per ISO 21930, 7.1.9 [4], appropriate activity and LCI primary and secondary data shall be used to model the wood resin product systems. LCI data should be as representative (technologically, geographically, and time-specific), complete, consistent, reproducible, and transparent as possible with regards to the goal and scope of the study [2], [3]. A detailed description of collected data and the data quality assessment regarding the ISO 14044 and ISO 21930 requirements [3] [4], is provided in Sections 4 to 10 and Annex B, Table B.1. Data quality is assessed based on its representativeness (technology coverage, geographic coverage, time coverage). Completeness, consistency, reproducibility, transparency, and uncertainty (see Table 2).

Table 2 Data quality requirements and assessments

Data Quality Requirements	Description
Technology Coverage	Data represents the prevailing technology in use in U.S. Whenever available, for all upstream and core material and processes, U.S. or North American typical or average industry LCI datasets were utilized (see Annex B). *Technological representativeness is characterized as "high".*
Geographic Coverage	The geographic region considered is the U.S. The geographic coverage of all LCI databases and datasets is provided in Annex B. *Geographical representativeness is characterized as "high".*
Time Coverage	Gate-to-gate activity data are representative as of 2019 (see Sections 4 to 10). - Generic data: the most appropriate LCI datasets were used as found in the U.S. LCI Database, ecoinvent v.3.7.1 database for US, North America and global, 2021. *Temporal representativeness is characterized as "medium" to "high".*
Completeness	All relevant, specific processes, including inputs (raw materials, energy, and additives) and outputs (emissions and production volume) were considered and modeled to provide an industry average for each of the wood resins. The relevant background materials and processes were taken from the U.S. LCI Database, ecoinvent v 3.7.1 LCI database for U.S. and North America, and modeled in SimaPro software v.9.2.0.2, 2021. The completeness of the cradle-to-gate process chain in terms of inputs/outputs is rigorously assessed and benchmarked for the resins of interest and documented in Section 3.2, Sections 4 to 10, and Annex A.

Data Quality Requirements	Description
Consistency	To ensure consistency, the LCI modeling of the production weighted input and output LCI data for each resin used the same LCI modeling structure. Crosschecks concerning the plausibility of mass and energy flows and molar ratios were continuously conducted. The LCA team conducted molar ratio checks, mass and energy balances at the facility level to maintain a high level of consistency.
Reproducibility	A high level of transparency is provided throughout the LCA report as the weighted average LCI profile is presented for each of the wood resins as well as key upstream inputs (e.g., methanol and resorcinol). Key primary (manufacturer specific) and secondary (generic) LCI data sources are summarized in Sections 4 to 10 and Annex A. External reproducibility of the LCA results is possible as a high level of transparency is provided throughout the LCA report and LCI data and sources are summarized in Annex B.
Transparency	Activity and background LCI datasets are transparently documented in the LCA report, including data sources (see Sections 4 to 10, and Annex B). Data are rounded to an appropriate number of significant digits (2 to 5).
Uncertainty	A *sensitivity check* was conducted to assess the reliability of the reported LCA results and conclusions by determining how they are affected by value choices in the data or assumptions on calculation of LCIA and energy indicator results. This study employed a parameterized mass allocation method to better partition the total environmental burden between the formaldehyde (precursor) and resin systems. A sensitivity analysis on allocation rules was conducted- see Sections 3.7 and 12 as well as Annex C. The sensitivity check also includes the results of the Monte Carlo uncertainty analysis (see Section 12 and Annex C).

3.7 Allocation Rules

The allocation rules in general conform to ISO 14044 [3], Clauses 4.3.4.1 and 4.3.4.2 and ISO 21930 [4], 7.2.5 Allocation for co-products.

The resin manufacturing facilities produce various resin types and, in some instances, precursors used in the production of formaldehyde-based wood resins as well as other industrial resins and as such allocation was necessary. “Mass” was deemed the most appropriate physical parameter for allocation of the total inputs/outputs of the plant production system between precursors (if applicable), the wood resins of interest and other co-products (non-wood sector adhesives) where applicable.

For the formaldehyde-based resin systems, Athena developed a parameterized mass allocation (PMA) method across multi-product formaldehyde-based resin systems to better partition (separate) the LCI data for the production of formaldehyde (precursor) from the resins production data instead of applying a default mass allocation method based solely on the total production quantities. Applying a default mass allocation basis typically reflects a “black box” method [1].

The parametrized modelling is commonly used in LCA studies [12]. The goal of this parametrized mass allocation method was to partition the environmetal burden of formaldehyde production from the resins to more accurately model formaldehyde production as its manufacture is key to the downstream resins in which it is a key component. Based on the scientific literature, stochiometry and Wilson 2009 [1] several gate-to-gate flows were partitioned based on a parametrized mass allocation approach- see Table 3. This method partitioned a number of flows as collected from the plant sample – electricity and natural gas use being key among them.

Partitioning of the environmental burden of formaldehyde production from the resins was required to allow for the application of the weighted average approach for precursor and resins production across three types of amino and phenol resin manufacturing facilities (purchased formaldehyde, on-site formaldehyde-Formox process; on-site formaldehyde-Silver catalyst process)- see Table 1. The environmental burden of formaldehyde production is included in module A1 (see Table 6).

For the reference year 2005, Wilson 2009 report states: "*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*" [1]. For the reference year 2019, the representative plant data indicated a 65% Formox and 35% Silver catalyst technology mix with 10% of the formaldehyde purchased off-site.

Table 3 Parametrized mass allocation approach (Baseline)

Resins and Formaldehyde (CH2O)	Material and formulation water Inputs[1]	Electricity allocation factors- purchased CH2O	Electricity allocation factors- on-site Silver process	Electricity allocation factors- on-site Formox process	Natural gas allocation factors	NOx allocation factors	Phenol allocation factors	Rest of Inputs/ Outputs[6]
Formaldehyde	PGF	n/a	1.7[2]	3.6[2]	0[3]	1.0[4]	0	1.0
UF resin	PGF	1.0	1.0	1.0	1.0	0	0	1.0
MUF resin	PGF	1.0	1.0	1.0	1.0	0	0	1.0
MF resin	PGF	1.0	1.0	1.0	1.0	0	0	1.0
PF resin	PGF	1.0	1.0	1.0	1.0	0	1.0[5]	1.0
PRF resin	PGF	1.0	1.0	1.0	1.0	0	1.0[5]	1.0
Other resins	n/a	1.0	1.0	1.0	1.0	0	0	1.0
Allocation approach	Plant generic formulation	Mass allocation	PMA	PMA	PMA	PMA	PMA	Mass allocation

Example:

Electricity consumption factors per resin and formaldehyde (on-site Formox process) are calculated as follows:

$\text{Electricity}_{\text{Total Facility}} = A_F*3.6*X+A_{UF}*1*X+A_{MUF}*1*X+A_{PF}*1*X+A_{PRF}*1*X+A_{MF}*1*X+A_{\text{Others}}*1*X$

Where,

A- stands for "annual production per formaldehyde or resin type" per facility.

X- stands for the "variable (in kWh/kg resin)" per facility. If X is equal to 50, then the electricity factors of formaldehyde, UF, MUF, MF, PF, PRF and other resins are 180, 50, 50, 50, 50, 50, and 50, respectively.

Similar formulas are used for all selected input/output flows.

Notes to Table 3:

[1] Plant generic formulations (PGF) are used for material and formulation water inputs.

[2] Electricity factor for formaldehyde production, Formox and Silver processes are around 4 and 2 times higher than amino and phenolic resin production, respectively. Therefore, parameterized mass allocation is applied based on ecoinvent 3.7.1 2021 and Wilson 2009 data. The electricity factor of Silver process is 100kWh/ 1,000 kg formaldehyde (100% solids) – see Table 39.3 [11]. The electricity factor of Formox process is 200-225 kWh/1,000 kg formaldehyde (100% solids) – see Table 39.3 [11]. The average electricity factor of amino and phenolic resin production (excluding the burden of formaldehyde production) is around 60 kWh/kg 100% solid resin [1].

[3] Formaldehyde production is an exothermic process and does not consume natural gas (produces steam as a by-product), hence the parameterized mass allocation is applied [11].
[4] NOx process-specific emissions are applicable for CH2O production only (Silver process), hence parameterized mass allocation is applied for NOx emissions-see [11], [1].
[5] Phenol emissions are applicable for PF and PRF resins production only, hence parameterized mass allocation is applied for phenol emissions [1].
[6] Mass allocation is applied for the rest of inputs/outputs.

Per ISO 21930 [4], by-product is defined as co-product from a process that is incidental or not intentionally produced and which cannot be avoided. Often, precursor production is exothermic (e.g., formaldehyde) with the excess heat (as steam) used downstream in the production of the final resin(s). No credit is allocated to the by-product (steam) of the selected product system that is consumed in the same facility. Allocation related to transport is based on the mass of transported inputs and outputs.

3.8 Impact Assessment Indicators Describing Main Environmental Impacts Derived from LCA

Per ISO 21930, 9.5.1 [4], the following impact assessment indicators are reported as described in Table 4.

Table 4 LCIA category indicators

Impact category	Category indicator	Unit (per Declared Unit)	Source of the characterization method	Level of site specificity selected	Environ-mental media
Climate change	Global warming potential (GWP 100)[1]	kg CO_2 – equiv.	TRACI 2.1 2012 updated with IPCC 2013, AR5[1]	Global	Air
Ozone depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11 equiv.	TRACI 2.1 2012/WMO:2003	Global	Air
Acidification	Acidification potential (AP)	kg SO_2 equiv.	TRACI 2.1 2012	North America	Air, Water
Eutrophication	Eutrophication potential (EP)	kg N equiv.	TRACI 2.1 2012	North America	Air, Water
Smog	Smog formation potential (SFP)	kg O_3 equiv.	TRACI 2.1 2012	North America	Air
Abiotic depletion potential,elements	Abiotic depletion potential,elements ADPelements	kg Sb eq	CML-baseline, v4.7 2016	Global	Resource use

Impact category	Category indicator	Unit (per Declared Unit)	Source of the characterization method	Level of site specificity selected	Environ-mental media
Abiotic depletion potential, fossil	Abiotic depletion potential, fossil ADP_f	MJ, LHV	CML-baseline, v4.7 2016	Global	Resource use

Note to Table 4:
[1] 100-year time horizon GWP factors (also known as GWP 100a) are provided by the IPCC 2013 Fifth Assessment Report (AR5). GWP 100 indicator results *exclude* biogenic CO_2 removal and emissions associated with any biobased products. There is no biogenic content in the declared wood resin products.

3.9 Inventory Indicators Describing Resource Use, Waste Categories and Output Flows

Per ISO 21930, 9.5.2 [4], the following mandatory resource use, waste categories and output flows are reported as described in Table 5.

Table 5 Parameters describing resource use, waste categories and output flows

Parameter	Unit (per Declared unit)
Resource Use	
RPR_E: Renewable primary resources used as energy carrier (fuel)	MJ, LHV
RPR_M: Renewable primary resources with energy content used as material	MJ, LHV
$NRPR_E$: Non-renewable primary resources used as an energy carrier (fuel)	MJ, LHV
$NRPR_M$: Non-renewable primary resources with energy content used as material	MJ, LHV
SM: Secondary materials	kg
RSF: Renewable secondary fuels	MJ, LHV
NRSF: Non-renewable secondary fuels	MJ, LHV
RE: Recovered energy	MJ, LHV
FW: Consumption of freshwater	m^3
Waste Categories	
HWD: Hazardous waste disposed	kg
NHWD: Non-hazardous waste disposed	kg
HLRW: High level radioactive waste, conditioned, to final repository	m^3
ILLRW: Intermediate and low level radioactive waste, conditioned, to final repository	m^3
Output Flows	
CRU: Components for re-use	kg
MR: Materials for recycling	kg
MER: Materials for energy recovery	kg
EE: Exported energy	MJ, LHV

4 Formaldehyde Production

Formaldehyde is a key precursor used in the production of thermoset resins used in the wood products sector. It is most often produced on-site at the amino and phenolic resin manufacturing location. Formaldehyde is produced industrially by the oxidation/dehydrogenation of methanol (Silver catalyst process) or by oxidation of methanol with air (Formox process, iron–molybdenum oxide catalyst) [11], [13]. The primary industry data underlying this study indicated a 65% Formox and 35% Silver catalyst technology mix with 10% of the formaldehyde purchased off-site. Both formaldehyde production technologies are exothermic with the excess steam typically used in downstream resin production [11], [13]. The key chemical input in the production of formaldehyde is methanol. It takes 1.2 kg of methanol to produce 1 kg of formaldehyde (100% solids basis) [1], [11]. This study drew on updated 2020 US methanol LCI data [14] – see Annex B, Table B.2.

Table 6 lists the input/output LCI flows used to produce 1,000 kg of formaldehyde (100% solids) reflecting the mix of both technologies across the industry sample. Table 7 presents the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of formaldehyde (100% solids). The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check- see Annex A, Table A.2. The LCI data were also benchmarked with ecoinvent v3.7.1 2021 data for formaldehyde production [15]- see Annex A, Table A.3. The most common wood resins are based on chemical reactions of formaldehyde with urea, melamine, phenol, resorcinol, or mixtures of them.

Table 6 Inputs and outputs for the production of 1,000 kg formaldehyde (100% solids)

Inputs/Outputs	Formaldehyde	Unit	Source of data[5)]
Material Inputs[1)]			
Methanol	1,151	kg	D
Water for Formaldehyde Production	51.0	kg	D
Energy Input			
Purchased Electricity	128.5	kWh	D,I
Liquified Propane Gas	0.018	liter	D,I
Water Consumption			
Water, fresh, for cooling and boiler make up	843.2	kg	I
Product and By-product Outputs			
Formaldehyde	1,000	kg	D
Emissions to Air[2)]			
PM-Filterable (PM-FIL)	9.7E-02	kg	D,I
PM10-Filterable (PM10-FIL)	9.1E-02	kg	D,I
PM2.5-Filterable (PM25-FIL)	6.8E-02	kg	D,I
Total NMVOC, non-methane volatile organic compounds	3.0E-01	kg	D,I
Formaldehyde	3.6E-02	kg	D,I
Methanol	1.1E-01	kg	D,I
Nitrogen oxides	4.7E-02	kg	D,I
Carbon monoxide[3)]	1.3E-04	kg	D,I
Emissions to Water[2)]			
TSS, total suspended solids	1.6E-04	kg	D,I
BOD5, biological oxygen demand	8.5E-05	kg	D,I
Solid Waste			
Non-hazardous waste to Landfill	3.8E+00	kg	D,I
Non-hazardous waste to Incineration	5.0E-01	kg	D,I
Non-hazardous waste to Recycling	9.5E-01	kg	D,I
Hazardous waste to Incineration	1.8E-02	kg	D,I
Liquid Waste			
Wastewater to treatment facility	8.5	kg	D,I

Notes to Table 6:

[1)] All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs.

[2)] Emissions to air and water consist of process-specific emissions (no fuel-combustions).

[3)] Carbon monoxide factor is calculated based on 65% Formox and 35% Silver processes (2019 RY) and ecoinvent CO factors for formaldehyde (Table 39.4, [11]).

[4)] PM-FIL, PM10-FIL and PM25-FIL stand for filterable particulate matter less than or equal to 30microns, 10microns, and 2.5microns in diameter, respectively.

[5)] D and I stand for direct and indirect data, respectively.

Table 7 Inbound and outbound transportation data for 1,000 kg formaldehyde (100% solids)

Transportation data	Per 1,000 kg Formaldehyde (100% solids)			
	Truck	Rail	Ship	Barge
	t.km	t.km	t.km	t.km
All material inputs (see Table 6)	132.8	442.7	0	0
Combination truck, diesel, short haul <200 mi	1.6			
Combination truck, diesel, long haul >200 mi	131.2			
All waste outputs (see Table 6)	4.4	0	0	0
Single unit truck, diesel, short haul < 200 mi	1.3E-03			
Single unit truck, diesel, long haul > 200 mi	4.4			

5 Urea Formaldehyde (UF) Resin

Urea Formaldehyde (UF) resins, known as amino resins, are typically used for interior use products such as particleboard, medium density fiberboard and hardwood plywood production [1], [8], [16], [19], [20]. "*Amino resins are condensates formed when carbonyl compounds react with compounds containing amino, imino, or amide groups, liberating water. Before they have hardened, these products consist principally of oligomers, which are also called prepolymers" [8]*. UF resins are formed by the reaction of urea and formaldehyde and other minor chemicals (<0.2% by weight, 100% solids) [1], [11], [21]. The UF is an amino resin produced via hydroxymethylation and condensation processes which is slightly exothermic [1], [8], [17], [18].

Table 6 presents the input chemicals used to produce UF resin and the achieved molar ratio of formaldehyde to urea as a check on the quality of the data for the reference year 2019 [1]. Similar to Wilson 2009 [1], the molar ratio was found to be at the lower end of the expected molar ratio range. Table 8 lists the input/output flows LCI used to produce 1,000 kg of UF resin (100% solids). Table 9 presents the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of UF resin (100% solids). The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check- see Annex A, Table A.2. The LCI data were also benchmarked with Wilson 2009 [1] and ecoinvent v3.7.1 2021 data for UF resin production [21], [11]- see Annex A, Table A.4.1 and A.4.2.

Table 8 UF resin (100% solids) – Input chemicals and molar ratio of formaldehyde to urea (RY=2019)

Input Chemicals	Molecular Formula	Resin
Urea (100%)[1]	$CO(NH_2)_2$	Urea-formaldehyde resin (100%)[2]
Formaldehyde (50-53%)	CH_2O	
Methanol (100%)	CH_3OH	
Formic acid (90%, 95%)	CH_2O_2	
Ammonium sulfate (35%)	$(NH_4)_2SO_4$	
Sodium hydroxide (25%-50%)	$NaOH$	
Water	H_2O	

UF resin (100% solids) - Molar ratio of formaldehyde to urea (RY=2019)

Inputs	Molar Mass (g/mol)	UF molar ratio check			
		Formulation mass-in g/kg resin (100% solids)	No. of moles	Molar ratio	Expected molar ratio range
Formaldehyde	30.0	406	14	1.1	1.1 to 1.8[3]
Urea	60.1	757	13		

Notes to Table 8:

[1] Solids content or active substance/solution strength of input chemicals into the plant. All chemical weights are given at either 100% non-volatile solids or dry – see Table 9.

[2] Solids content of reported resin data.

[3] Expected molar ratio range - see Annex A, Table A.1 and A.4.2 for details.

Table 9 Inputs and outputs for the production of 1,000 kg UF resin (100% solids)

Inputs/Outputs	UF resin	Unit	Source of data[3)]
Material Inputs[1)]			
Formaldehyde	406.1	kg	D
Urea	757.2	kg	D
Methanol	6.2E-03	kg	D
Formic acid	0.19	kg	D
Ammonium sulfate	7.6E-03	kg	D
Sodium hydroxide	2.1	kg	D
Other Additives	0.035	kg	D
Water for Resin Production	8.8	kg	D
Energy Input			
Purchased Electricity	45.1	kWh	D,I
Natural Gas	26.8	m³	D,I
Liquified Propane Gas	0.018	liter	D,I
Water Consumption			
Water, fresh, for cooling and boiler make up	843.2	kg	I
Product and By-product Outputs			
UF- Urea–formaldehyde	1,000	kg	D
Emissions to Air[2)]			
PM-Filterable (PM-FIL)	1.7E-01	kg	D,I
PM10-Filterable (PM10-FIL)	1.7E-01	kg	D,I
PM2.5-Filterable (PM25-FIL)	1.5E-01	kg	D,I
Total NMVOC, non-methane volatile organic compounds	1.9E-01	kg	D,I
Formaldehyde	5.0E-02	kg	D,I
Methanol	8.0E-02	kg	D,I
Emissions to Water[2)]			
TSS, total suspended solids	3.4E-05	kg	D,I
BOD5, biological oxygen demand	2.4E-05	kg	D,I
Solid Waste			
Non-hazardous waste to Landfill	1.3E+00	kg	D,I
Non-hazardous waste to Incineration	2.8E-01	kg	D,I
Non-hazardous waste to Recycling	2.5E-02	kg	D,I
Hazardous waste to Incineration	2.2E-02	kg	D,I
Liquid Waste			
Wastewater to treatment facility	1.3	kg	D,I

Notes to Table 9:

[1)] All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs.

[2)] Emissions to air and water consist of process-specific emissions (no fuel-combustions).

[3)] D and I stand for direct and indirect data, respectively.

Table 10 Inbound and outbound transportation data for 1,000 kg UF resin (100% solids)

Transportation data	**Per 1,000 kg UF resin (100% solids)**			
	Truck	**Rail**	**Ship**	**Barge**
	t.km	t.km	t.km	t.km
All material inputs (see Table 9)	348.7	42.4	0	0
Combination truck, diesel, short haul <200 mi	1.4			
Combination truck, diesel, long haul >200 mi	347.2			
All waste outputs (see Table 9)	1.1	0	0	0
Single unit truck, diesel, short haul < 200 mi	4.8E-03			
Single unit truck, diesel, long haul > 200 mi	1.126			

6 Melamine Urea Formaldehyde (MUF) Resin

Melamine Urea Formaldehyde (MUF) resins, known as amino resins, are similarly used for interior use products such as particleboard, medium density fiberboard and hardwood plywood production but impart greater moisture and water resistance than UF resins [1], [8], [16], [19], [22]. The greater the content of melamine in the formulation the greater the moisture resistance [1]. "*The chemistry of the MUF adhesives is similar to the MF and UF adhesives, but more variations exist due to the ratio of melamine to urea, the sequence for addition of the components, temperature, pH, and time factors. In summary, the MUF adhesives, depending on the melamine-to-urea ratio, can be considered as a less expensive MF that has lower durability or as a more expensive UF that has better water resistance. The MUF adhesives can replace other adhesives that are used for some exterior applications*" [24].

"*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"* [1]. For 2019 reference year, the content of melamine in the formulation resulted in 2% by weight (100% solids). MUF resins are formed by the reaction of melamine, urea and formaldehyde and other minor chemicals (<1.5% by weight, 100% solids) [1], [8], [19], [22]. Like UF, MUF is an amino resin produced via hydroxymethylation and condensation processes which is slightly exothermic [1], [11].

Table 11 presents the input chemicals used to produce MUF resin and the achieved molar ratio of formaldehyde to urea and melamine as a check on the quality of the data [1]. Similar to Wilson 2009 [1], the molar ratio was found to be at the lower end of the expected molar range.

Table 12 lists the input/output flows LCI used to produce 1,000 kg of MUF resin (100% solids). Table 13 presents the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of MUF resin (100% solids). The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check- see Annex A, Table A.2. The LCI data were also benchmarked with Wilson 2009 [1] and ecoinvent v3.7.1 2021 data for MUF resin production [23]- see Annex A, Table A.5.1 and A.5.2.

Table 11 MUF resin (100% solids) – Input chemicals and molar ratio of formaldehyde to urea and melamine (RY=2019)

Input Chemicals	**Molecular Formula**	**Resin**
Melamine (100%)1)	$C_3N_3(NH_2)_3$	Melamine-urea-formaldehyde resin (100%)2)
Urea (100%)	$CO(NH_2)_2$	
Formaldehyde (50-53%)	CH_2O	
Methanol (100%)	CH_3OH	
Formic acid (95%)	CH_2O_2	
Ammonium sulfate (35%)	$(NH_4)_2SO_4$	
Sodium hydroxide (30%-50%)	$NaOH$	
Ammonium hydroxide (28%)	NH_4OH	
Water	H_2O	

MUF resin (100% solids) - Molar ratio of formaldehyde to urea plus melamine (RF=2019)

Inputs	Molar Mass (g/mol)	MUF molar ratio check			
		Formulation mass-in g/kg resin (100% solids)	No. of moles	Molar ratio	Expected molar ratio range
Formaldehyde	30.0	390	13	1.1	1.1 to 1.33)
Urea	60.1	674	11		
Melamine	126.1	23	0.2		

Notes to Table 11:

1) Solids content or active substance/solution strength of input chemicals into the plant. All chemical weights are given at either 100% non-volatile solids or dry – see Table 12.

2) Solids content of reported resin data.

3) Expected molar ratio range- see Annex A, Table A.1 and A.5.2 for details.

Table 12 Inputs and outputs for the production of 1,000 kg MUF resin (100% solids)

Inputs/Outputs1)	**MUF resin**	**Unit**	**Source of data**3)
Material Inputs			
Melamine	22.8	kg	D
Urea	673.5	kg	D
Formaldehyde	390.5	kg	D
Methanol	0.08	kg	D
Formic acid	0.02	kg	D
Ammonium sulfate	0.085	kg	D
Sodium hydroxide	0.55	kg	D
Ammonium Hydroxide	2.3	kg	D
Other Additives- Sodium Chloride	11.5	kg	D
Water for Resin Production	31.9	kg	D
Energy Input			
Purchased Electricity	44.1	kWh	D,I
Natural Gas	28.0	m³	D,I
Liquified Propane Gas	0.018	liter	D,I
Water Consumption			
Water, fresh, for cooling and boiler make up	843.2	kg	I
Product and By-product Outputs			
MUF- Melamine–urea–formaldehyde	1,000	kg	D
Emissions to Air2)			
PM-Filterable (PM-FIL)	6.0E-02	kg	D,I
PM10-Filterable (PM10-FIL)	5.2E-02	kg	D,I
PM2.5-Filterable (PM25-FIL)	2.0E-02	kg	D,I
Total NMVOC, non-methane volatile organic compounds	3.1E-01	kg	D,I
Formaldehyde	2.2E-02	kg	D,I
Methanol	1.1E-01	kg	D,I
Emissions to Water2)			
TSS, total suspended solids	7.7E-05	kg	D,I
BOD5, biological oxygen demand	5.5E-05	kg	D,I
Solid Waste			
Non-hazardous waste to Landfill	2.4E+00	kg	D,I
Non-hazardous waste to Incineration	6.1E-01	kg	D,I
Non-hazardous waste to Recycling	7.7E-01	kg	D,I
Hazardous waste to Incineration	1.4E-04	kg	D,I
Liquid Waste			
Wastewater to treatment facility	5.3	kg	D,I

Notes to Table 12:
1) All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs.
2) Emissions to air and water consist of process-specific emissions (no fuel-combustions).
3) D and I stand for direct and indirect data, respectively.

Table 13 Inbound and outbound transportation data for 1,000 kg MUF resin (100% solids)

Transportation data	**Per 1,000 kg** **MUF resin (100% solids)**			
	Truck	**Rail**	**Ship**	**Barge**
	t.km	t.km	t.km	t.km
All material inputs (see Table 12)	79.4	398.4	0	0
Combination truck, diesel, short haul <200 mi	0.282			
Combination truck, diesel, long haul >200 mi	79.1			
All waste outputs (see Table 12)	3.1	0	0	0
Single unit truck, diesel, long haul > 200 mi	3.1			

7 Melamine Formaldehyde (MF) Resin

Melamine–formaldehyde resins, known as amino resins, are most commonly used for exterior and semi-exterior plywood and particleboard, and for finger joints *[22], [24]. “Unlike UF adhesives, MF adhesives have acceptable water resistance, but they are much lighter in color than the others.*” [22]. “*When MF resin is used as wood adhesive it exhibits good bonding strength, high stability toward hydrolysis, and low formaldehyde emission*” [25]. MU is an amino resin produced via hydroxymethylation and condensation processes which is slightly exothermic [11].

“T*he condensation reaction of melamine (I) with formaldehyde is similar to but different from the reaction of formaldehyde with urea. As for urea, formaldehyde first attacks the amino groups of melamine, forming methylol compounds. However, formaldehyde addition to melamine occurs more easily and completely than does addition to urea. reaction. Another important difference is that MF condensation to give resins, and their curing, can occur not only under acid conditions, but also under neutral or even slightly alkaline conditions*” [22], [25].

Table 14 presents the input chemicals used to produce MF resin and the achieved molar ratio of formaldehyde to melamine as a check on the quality of the data [1]. The molar ratio was found to be within the expected molar range.

Table 15 lists the input/output flows LCI used to produce 1,000 kg of MF resin (100% solids). Table 16 presents the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of MF resin (100% solids). The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check- see Annex A, Table A.2. The LCI data were also benchmarked with ecoinvent 3.7.1 2021 [26] for MF resin production- see Annex A, Table A.6.1 and A.6.2.

Table 14 MF resin (100% solids) – Input chemicals and molar ratio of formaldehyde to melamine (RY=2019)

Input Chemicals	**Molecular Formula**	**Resin**
Melamine (100%)1)	$C_3N_3(NH_2)_3$	Melamine-formaldehyde resin (100%)2)
Formaldehyde (50-53%)	CH_2O	
Methanol (100%)	CH_3OH	
Water	H_2O	

MF 100% solid - Molar ratio of formaldehyde to melamine (RF=2019)

Inputs	Molar Mass (g/mol)	MF molar ratio check			
		Formulation mass-in g/kg resin (100% solids)	No. of moles	Molar ratio	Expected molar ratio range
Formaldehyde	30.03	276	9	1.6	1.5 to 2.03)
Melamine	126.12	727	6		

Notes to Table 14:

1) Solids content or active substance/solution strength of input chemicals into the plant. All chemical weights are given at either 100% non-volatile solids or dry – see Table 15.

2) Solids content of reported resin data.

3) Expected molar ratio range- see Annex A, Table A.1 and A.6.2 for details.

Table 15 Inputs and outputs for the production of 1,000 kg MF resin (100% solids)

Inputs/Outputs	MF resin	Unit	Source of data[4)]
Material Inputs[1)]			
Melamine	727.3	kg	D
Formaldehyde	275.9	kg	D
Urea	0.038	kg	D
Methanol[2)]	108.3	kg	D
Energy Input			
Purchased Electricity	69.0	kWh	D,I
Natural Gas	26.7	m^3	D,I
Liquified Propane Gas (LPG)	0.018	liter	D,I
Water Consumption			
Water, fresh, for cooling and boiler make up	843.2	kg	I
Product and By-product Outputs			
MF- Melamine–formaldehyde	1,000	kg	D
Emissions to Air[3)]			
PM-Filterable (PM-FIL)	2.5E-02	kg	D,I
PM10-Filterable (PM10-FIL)	2.5E-02	kg	D,I
PM2.5-Filterable (PM25-FIL)	2.5E-02	kg	D,I
Total NMVOC, non-methane volatile organic compounds	2.6E-01	kg	D,I
Formaldehyde	1.9E-02	kg	D,I
Methanol	2.4E-01	kg	D,I
Emissions to Water[3)]			
TSS, total suspended solids	3.4E-05	kg	D,I
BOD5, biological oxygen demand	2.4E-05	kg	D,I
Solid Waste			
Non-hazardous waste to Landfill	1.0E+00	kg	D,I
Non-hazardous waste to Incineration	1.9E-01	kg	D,I
Non-hazardous waste to Recycling	2.2E-01	kg	D,I
Hazardous waste to Incineration	9.4E-03	kg	D,I
Liquid Waste			
Wastewater to treatment facility	1.3	kg	D,I

Notes to Table A15:

1) All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs.

2) It should be noted the effect that the methanol has on the melamine-formaldehyde reaction is to inhibit the formation of fully methylolated melamine-formaldehyde reaction products.

3) Emissions to air and water consist of process-specific emissions (no fuel-combustions).

4) D and I stand for direct and indirect data, respectively.

Table 16 Inbound and outbound transportation data for 1,000 kg MF resin (100% solids)

Transportation data	Per 1,000 kg MF resin (100% solids)			
	Truck t.km	**Rail** t.km	**Ship** t.km	**Barge** t.km
All material inputs (see Table 15)	374.0	344.4	0	0
Combination truck, diesel, short haul <200 mi	116.9			
Combination truck, diesel, long haul >200 mi	257.1			
All waste outputs (see Table 15)	0.5	0	0	0
Single unit truck, diesel, long haul > 200 mi	0.523			

8 Phenol Formaldehyde (PF) Resin

Phenol Formaldehyde (PF) resins, known as phenolic resins, impart higher moisture resistance than UF and MUF and are used in exterior use products such as softwood plywood, oriented strand board and laminated veneer lumber products [1], [9], [24]. "*Phenolic resins are polycondensation products of phenols and aldehydes, in particular phenol and formaldehyde*" [9]. "*For all PF adhesives, phenol is reacted with formaldehyde or a formaldehyde precursor under the proper conditions to produce an oligomer that can undergo further polymerization during the setting process. There are two basic types of oligomers, novolaks that have a formaldehyde/phenol (F/P) ratio of less than 1 and are generally made under acidic conditions, and resole resins made under basic conditions with F/P ratios of greater than 1. Although at first glance the acid and base processes may seem to be similar, the chemical reactions and the polymer structures are quite different. For most wood adhesive applications, the resole resins are used because they provide a soluble adhesive that has good wood wetting properties, and the cure is delayed until activated by heat allowing product assembly time*" [24].

Table 17 presents the input chemicals used to produce PF resin and the achieved molar ratio of formaldehyde to phenol as a check on the quality of the data [1]. Similar to Wilson 2009 [1], the molar ratio was found to be within the expected molar range.

Table 18 lists the input/output flows LCI used to produce 1,000 kg of PF resin (100% solids). Table 19 presents the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of PF resin (100% solids). The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check- see Annex A, Table A.2. The LCI data were also benchmarked with Wilson 2009 [1] for PF resin production - see Annex A, Table A.7.1 and A.7.2.

Table 17 PF resin (100% solids) – Input chemicals and molar ratio of formaldehyde to phenol (RY=2019)

Input Chemicals	**Molecular Formula**	**Resin**
Phenol (100%)[1]	C_6H_6O	Phenol-formaldehyde resin (100%)[2]
Formaldehyde (50-53%)	CH_2O	
Methanol (100%)	CH_3OH	
Sodium hydroxide (50%)	NaOH	
Urea (100%)	$CO(NH_2)_2$	
Water	H_2O	

PF 100% solid - Molar ratio of formaldehyde to phenol (RF=2019)

Inputs	Molar Mass (g/mol)	PF molar ratio check			
		Formulation mass- in g/kg resin (100% solids)	No. of moles	Molar ratio	Expected molar ratio range
Formaldehyde	30.0	397	13	2.2	2.0 to 2.5[3]
Phenol	94.1	557	6		

Notes to Table 17:

[1] Solids content or active substance/solution strength of input chemicals into the plant. All chemical weights are given at either 100% non-volatile solids or dry – see Table 18.

[2] Solids content of reported resin data.

[3] Expected molar ratio range- see Annex A, Table A.1 and A.7.2 for details.

Table 18 Inputs and outputs for the production of 1,000 kg PF resin (100% solids)

Inputs/Outputs	PF resin	Unit	Source of data[3)]
Material Inputs[1)]			
Phenol	556.5	kg	D
Formaldehyde	397.2	kg	D
Sodium hydroxide	103.8	kg	D
Urea	57.6	kg	D
Other Additives	6.2	kg	D
Water for Resin Production	439.7	kg	D
Energy Input			
Purchased Electricity	46.1	kWh	D,I
Natural Gas	33.4	m³	D,I
Liquified Propane Gas	0.018	liter	D,I
Water Consumption			
Water, fresh, for cooling and boiler make up	843.2	kg	I
Product and By-product Outputs			
PF- Phenol–formaldehyde	1,000	kg	D
Emissions to Air[2)]			
PM-Filterable (PM-FIL)	1.1E-01	kg	D,I
PM10-Filterable (PM10-FIL)	1.0E-01	kg	D,I
PM2.5-Filterable (PM25-FIL)	5.0E-02	kg	D,I
Total NMVOC, non-methane volatile organic compounds	4.6E-01	kg	D,I
Phenol	1.9E-02	kg	D,I
Formaldehyde	4.2E-02	kg	D,I
Methanol	1.8E-01	kg	D,I
Emissions to Water[2)]			
TSS, total suspended solids	1.8E-04	kg	D,I
BOD5, biological oxygen demand	1.1E-04	kg	D,I
Solid Waste			
Non-hazardous waste to Landfill	2.9E+00	kg	D,I
Non-hazardous waste to Incineration	1.0E+00	kg	D,I
Non-hazardous waste to Recycling	4.5E-01	kg	D,I
Hazardous waste to Incineration	3.2E-02	kg	D,I
Liquid Waste			
Wastewater to treatment facility	7.8	kg	D,I

Notes to Table 18:

[1)] All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs.

[2)] Emissions to air and water consist of process-specific emissions (no fuel-combustions).

[3)] D and I stand for direct and indirect data, respectively.

Table 19 Inbound and outbound transportation data for 1,000 kg PF resin (100% solids)

Transportation data	Per 1,000 kg PF resin (100% solids)			
	Truck t.km	Rail t.km	Ship t.km	Barge t.km
All material inputs (see Table 18)	646.9	240.9	0	0
Combination truck, diesel, short haul <200 mi	18.8			
Combination truck, diesel, long haul >200 mi	628.1			
All waste outputs (see Table 18)	4.1	0	0	0
Single unit truck, diesel, short haul < 200 mi	2.2E-04			
Single unit truck, diesel, long haul > 200 mi	4.1			

9 Phenol Resorcinol Formaldehyde (PRF) Resin

Phenol Resorcinol Formaldehyde (PRF) resins, known as phenolic resins, are used to produce glued laminated timbers and I-Joists as they have high mechanical stability and are highly water-resistant [1], [9], [24].

"*The chemical 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" [1].* "*Resorcinol (1,3-dihydroxybenzene) reacts particularly rapidly with formaldehyde and gives resins, which can be crosslinked even in an alkaline medium at room temperature*" [9]. "*Because phenol and resorcinol have three reactive sites, they are able to cross-link to form a thermosetting adhesive*" [24].

Table 20 presents the input chemicals used to produce PRF resin and the achieved molar ratio of formaldehyde to phenol and resorcinol as a check on the quality of the data [1]. Similar to Wilson 2009 [1], the molar ratio was found to be less than one and within the expected molar range.

Table 21 lists the input/output flows LCI used to produce 1,000 kg of PRF resin (100% solids). Table 22 presents the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of PRF resin (100% solids). The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check- see Annex A, Table A.2. The LCI data were also benchmarked with Wilson 2009 for PRF resin production [1]- see Annex A, Table A.8.1 and A.8.2.

It is noted that Wilson's 2009 study did not account for the environmental burden of resorcinol production in the LCA results reported for PRF resin as resorcinol LCI data were not available- see Table 5.9 [1]. Neither ecoinvent 3.7.1 2021 nor U.S. LCI Database do contain a LCI dataset for resorcinol production. For this study, Athena developed a generic LCI dataset for the resorcinol input based on stoichiometry and various scientific literature - see Annex B, Table B.3.

Table 20 PRF resin (100% solids) – Input chemicals and molar ratio of formaldehyde to phenol and resorcinol (RY=2019)

Input Chemicals	**Molecular Formula**	**Resin**
Phenol (100%)[1]	C_6H_6O	Phenol-resorcinol-formaldehyde resin (100%)[2]
Resorcinol (100%)	$C_6H_6O_2$	
Formaldehyde (50-53%)	CH_2O	
Methanol (100%)	CH_3OH	
Ethanol (100%)	C_2H_6O	
Sodium hydroxide (50%)	NaOH	
Water	H_2O	

PRF 100% solid - Molar ratio of formaldehyde to phenol plus resorcinol (RF=2019)

Inputs	Molar Mass (g/mol)	PRF molar ratio check			
		Formulation mass-in g/kg resin (100% solids)	No. of moles	Molar ratio	Expected molar ratio range
Formaldehyde	30.0	145	5	0.5	< 1.0[3]
Phenol	94.1	545	6		
Resorcinol	110.1	345	3		

Notes to Table 20:

[1] Solids content or active substance/solution strength of input chemicals into the plant. All chemical weights are given at either 100% non-volatile solids or dry – see Table 21.

[2] Solids content of reported resin data.

[3] Expected molar ratio range- see Annex A, Table A.1 and A.8.2 for details.

Table 21 Inputs and outputs for the production of 1,000 kg PRF resin (100% solids)

Inputs/Outputs	PRF resin	Unit	Source of data[3)]
Material Inputs[1)]			
Phenol	545.5	kg	D
Resorcinol	345.0	kg	D
Formaldehyde	144.5	kg	D
Ethanol	7.8	kg	D
Sodium hydroxide	31.8	kg	D
Water for Resin Production	529.8	kg	D
Energy Input			
Purchased Electricity	49.9	kWh	D,I
Natural Gas	37.2	m³	D,I
Liquified Propane Gas	0.018	liter	D,I
Water Consumption			
Water, fresh, for cooling and boiler make up	843.2	kg	I
Product and By-product Outputs			
PRF- Phenol–resorcinol–formaldehyde	1,000	kg	D
Emissions to Air[2)]			
PM-Filterable (PM-FIL)	7.6E-02	kg	D,I
PM10-Filterable (PM10-FIL)	7.6E-02	kg	D,I
PM2.5-Filterable (PM25-FIL)	7.6E-02	kg	D,I
Total NMVOC, non-methane volatile organic compounds	1.6E-01	kg	D,I
Phenol	4.9E-02	kg	D,I
Formaldehyde	5.4E-02	kg	D,I
Methanol	5.9E-02	kg	D,I
Emissions to Water[2)]			
TSS, total suspended solids	1.8E-04	kg	D,I
BOD5, biological oxygen demand	1.1E-04	kg	D,I
Solid Waste			
Non-hazardous waste to Landfill	1.0E+00	kg	D,I
Non-hazardous waste to Incineration	2.1E-01	kg	D,I
Non-hazardous waste to Recycling	2.2E-01	kg	D,I
Hazardous waste to Incineration	6.7E-02	kg	D,I
Liquid Waste			
Wastewater to treatment facility	7.8	kg	D,I

Notes to Table 21:

[1)] All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs.

[2)] Emissions to air and water consist of process-specific emissions (no fuel-combustions).

[3)] D and I stand for direct and indirect data, respectively.

Table 22 Inbound and outbound transportation data for 1,000 kg PRF resin (100% solids)

Transportation data	Per 1,000 kg PRF resin (100% solids)			
	Truck t.km	Rail t.km	Ship t.km	Barge t.km
All material inputs (see Table 21)	2,684.8	697.4	0	0
Combination truck, diesel, short haul <200 mi	2.1			
Combination truck, diesel, long haul >200 mi	2,682.7			
All waste outputs (see Table 21)	1.7	0	0	0
Single unit truck, diesel, short haul < 200 mi	5.8E-04			
Single unit truck, diesel, long haul > 200 mi	1.675			

10 Emulsion Polymer Isocyanate (EPI) and Polymer Emulsion Polyurethane (PEP) Adhesives

Emulsion Polymer Isocyanate (EPI) is a two-part adhesive system that is mixed prior to use and is based on an emulsion polymer (base) and an isocyanate hardener (cross linker) [20],[24], [29], [31]- see Table 23. "*The water-based emulsion adhesives with isocyanate as crosslinker are used in many parts of the world for production of different types of wood-based products such as: solid wood panels of different types, parquet, window frames, furniture parts, plywood, finger joints and load-bearing constructions like glulam beams and I-beams*" [27]. "*The advantages obtained by the use of EPI adhesives are fast-setting speed, cold curing, light-colored glueline, low creep of the glueline, and high moisture resistance. EPI adhesives give very good adhesion and are, because of this, ideally suited for gluing difficult wood species. EPI adhesives can also be used for gluing of wood to metal*" [31].

Polymer emulsion polyurethane (PEP) is a two-part system based on polyurethane adhesive (cross linker) blended with emulsion polymer (base) [24], [30]. Prior to use, the base must be thoroughly mixed with the cross linker with specified mixing ratio.

"*In the USA both standard EPI adhesives, with emulsion adhesive and pMDI, and polyurethane emulsion polymers (PEPs) are used for production of I-beams. These adhesive systems fulfill all the requirements for a structural adhesive*" [27]. PEPs are used successfully on structural finger joints and wooden I-joists, as well as web-to-web applications for making I-joists where no preparation is needed (butt joints).

The water-based polymer emulsion component is the main adhesive component in EPI adhesives. Generally, it consists of water, poly(vinyl alcohol) (PVA), one or more water-based emulsions (e.g. polyvinyl acetate, acrylic-based polymer latices), fillers (e.g. $CaCO_3$, clay) and a number of additives such as defoamers, dispersing agents and biocides, and other additives [27]. "*Fillers in EPI adhesive formulations are used to reduce the cost of the adhesive systems, to increase the solids content of the adhesive and to improve the gap filling properties and heat resistance of the cured glueline*" [27]. Isocyanates are used as a cross-linker in EPI adhesive systems with MDI being the preferred isocyanate due to its high reactivity and low vapor pressure [27], [28]. The most commonly form of MDI used in EPI adhesives is polymeric MDI (pMDI) [27], [28]. "*The mixing ratio of the water-based emulsion component and the isocyanate is commonly 100 parts by weight (pbw) adhesive to 10–20 pbw isocyanate, although dosages down to 5 pbw of isocyanate are also used*" [27].

The polyurethane adhesive component is the main adhesive component in PEP adhesives. Generally, it consists of polyol, isocyanates, and a number of additives such as defoamers, catalysts and inhibitors and other additives [30]. The same water-based polymer emulsion component (base) is used for the production of EPI and PEP.

Within the manufacturers sample for 2019 reference year, some facilities produce more than one base polymer and more than one adhesive type while purchasing the upstream cross link portion of the adhesive while others produce both parts of the adhesive of interest; i.e., the base polymer and the cross linker. For purposes of this LCA project and informed by our plant sample data, the Institute elected to develop a generic plant model whereby the base polymer as well as the cross-linker isocyanate is produced within the same facility (i.e., in the foreground) while all other inputs are sourced externally. This approach in conjunction with the aggregation of some other proprietary inputs fulfills the proprietary data confidentiality as requested by the resins manufactures. This approach does not impact the accuracy of the cradle to gate LCA results for EPI and PEP in any form.

The LCI survey data were analyzed for data quality by assessing for outliers and conducting the mass balance check. The LCI data were also benchmarked with K. Grøstad and A. Pedersen 2010 [27] and were found to be within the range. It is noted that EPI and PEP LCI datasets are not available in U.S. LCI Database or ecoinvent 3.7.1 2021.

Tables 24 and 25 list the input/output flows LCI used to produce 1,000 kg of EPI and PEP resins (100% solids), respectively. Tables 26 and 27 present the related inbound and outbound transportation mode and tkm data to produce 1,000 kg of EPI and PEP resins (100% solids), respectively.

Table 23 EPI and PEP resins (100% solids) – Input chemicals (RY=2019)

Input Chemicals	EPI resin	Input Chemicals	PEP resin
Base-Water-based polymer emulsion (50%)1)	Emulsion-polymer isocyanate (100%)2)	Base-Water-based polymer emulsion (50%)1)	Polymer emulsion polyurethane (100%)2)
Cross-linker- Methylene diphenyl diisocyanate (MDI)-based isocyanate (100%)		Cross-linker- Polyurethane (100%)	

Notes to Table 23:
1) Solids content or active substance/solution strength of input chemicals into the plant. All chemical weights are given at either 100% non-volatile solids or dry – see Tables 24 and 25.
2) Solids content of reported resin data.

Table 24 Inputs and outputs for the production of 1,000 kg EPI resin (100% solids)

Inputs/Outputs	EPI resin	Unit	Source of data4)
Material Inputs2)			
Base-Water-based polymer emulsion	759.0	kg	D,I
Cross-Linker- Methylene diphenyl diisocyanate (MDI)-based isocyanate	241.0	kg	D,I
Energy Input1)			
Purchased Electricity	137.9	kWh	D,I
Natural gas	79.2	m^3	D,I
Liquified Propane Gas	1.6	liter	D,I
Water Consumption1)			
Water, total	639.7	liter	I
Product and By-product Outputs			
EPI- Emulsion-polymer isocyanate resin	1,000	kg	D,I
Emissions to Air1) 3)			
PM10-Filterable (PM10-FIL)	1.5E-01	kg	D,I
Total NMVOC, non-methane volatile organic compounds	8.7E-02	kg	D,I
Total HAP, hazardous air pollutants	2.2E-03	kg	D,I
Emissions to Water1) 3)			
TSS, total suspended solids	2.4E+00	kg	D,I
Solid Waste1)			
Non-hazardous waste to Landfill	1.5E+01	kg	D,I
Non-hazardous waste to Incineration	3.9E+00	kg	D,I
Non-hazardous waste to Recycling	8.0E+00	kg	D,I
Hazardous waste to Incineration	1.6E+00	kg	D,I

Notes to Table 24:
1) Data presents the total energy input, water consumption, emissions to air, emissions to water, and solid waste for the production of 2-parts EPI resin (base and cross-linker). Data are rolled up for confidentiality reasons.

[2] All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs. Chemicals used in both base and cross-linker production are not presented for confidentiality reasons.
[3] Emissions to air and water consist of process-specific emissions (no fuel-combustions).
[4] D and I stand for direct and indirect data, respectively.

Table 25 Inputs and outputs for the production of 1,000 kg PEP resin (100% solids)

Inputs/Outputs	PEP resin	Unit	Source of data[4]
Material Inputs[2]			
Base- Water-based polymer emulsion	101.1	kg	D,I
Cross-Linker- Polyurethane	898.9	kg	D,I
Energy Input[1]			
Purchased Electricity	123.4	kWh	D,I
Natural gas	58.3	m³	D,I
Liquified Propane Gas	2.1	liter	D,I
Water Consumption[1]			
Water, total	88.1	liter	I
Product and By-product Outputs			
PEP- Polymer emulsion polyurethane	1,000	kg	D,I
Emissions to Air[1) 3]			
PM10-Filterable (PM10-FIL)	6.6E-02	kg	D,I
Total NMVOC, non-methane volatile organic compounds	4.0E-02	kg	D,I
Total HAP, hazardous air pollutants	1.2E-03	kg	D,I
Emissions to Water[1) 3]			
TSS, total suspended solids	1.5E-02	kg	D,I
Solid Waste[1]			
Non-hazardous waste to Landfill	2.5E+01	kg	D,I
Non-hazardous waste to Incineration	8.2E+00	kg	D,I
Non-hazardous waste to Recycling	1.1E+00	kg	D,I
Hazardous waste to Incineration	2.1E-01	kg	D,I

Notes to Table 25:
[1] Data presents the total energy input, water consumption, emissions to air, emissions to water, and solid waste for the production of 2-parts PEP resin (base and cross-linker). Data are rolled up for confidentiality reasons.
[2] All chemical weights given at either 100% non-volatile solids or dry. Plant generic formulations (PGF) are used for material and formulation water inputs. Chemicals used in both base and cross-linker production are not presented for confidentiality reasons.
[3] Emissions to air and waster consist of process-specific emissions (no fuel-combustions).
[4] D and I stand for direct and indirect data, respectively.

Table 26 Inbound and outbound transportation data for 1,000 kg EPI resin (100% solids)

Transportation data	Per 1,000 kg EPI Resin (100% solids)			
	Truck t.km	Rail t.km	Ship t.km	Barge t.km
All material inputs (see Table 24)	1,314.7	0	0	0
Combination truck, diesel, short haul <200 mi	64.2			
Combination truck, diesel, long haul >200 mi	1,250.5			
All waste outputs (see Table 24)	4.2	0	0	0
Single unit truck, diesel, short haul < 200 mi	2.0			
Single unit truck, diesel, long haul > 200 mi	2.2			

Table 27 Inbound and outbound transportation data for 1,000 kg PEP resin (100% solids)

Transportation data	Per 1,000 kg PEP Resin (100% solids)			
	Truck t.km	Rail t.km	Ship t.km	Barge t.km
All material inputs (see Table 25)	296.2	0	0	0
Combination truck, diesel, short haul <200 mi	127.1			
Combination truck, diesel, long haul >200 mi	169.0			
All waste outputs (see Table 25)	1.7	0	0	0
Single unit truck, diesel, short haul < 200 mi	1.5			
Single unit truck, diesel, long haul > 200 mi	0.2			

11 LCA Results

This section summarizes the life cycle impact assessment (LCIA) results including resource use and waste generated metrics based on the cradle-to-gate life cycle inventory inputs and outputs analysis. *It should be noted that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks [3].*

Tables 28 to 34 present the cradle-to-gate LCA results per ISO 21930 [4] for UF, MUF, MF, PF, PRF, EPI and PEP resins, respectively. The cradle-to-gate LCA results for formaldehyde are presented in Table 34. For the amino and phenolic resins, LCA results are reported by information module (A1-A3). Per ISO 21930, 7.1.7.1 [4], "*individual indicators for information modules A1, A2 and A3 may be aggregated to a total for each indicator in the production stage*". For EPI and PEP, LCA results are only presented for the total (A1 to A3) as manufacturers consider this information proprietary.

Table 28 Cradle-to-gate production stage (A1-A3) LCA Results – 1,000 kg of UF resin (100% solids)

Impact category and inventory indicators	**Unit**	**A1**	**A2**	**A3**	**Total**
Global warming potential, GWP 100[1)]	kg CO_2 eq	1,399	33.6	97.1	**1,530**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	3.1E-04	1.4E-09	1.2E-05	**3.2E-04**
Smog formation potential, SFP[1)]	kg O_3 eq	62.5	11.4	3.0	**77.0**
Acidification potential, AP[1)]	kg SO_2 eq	5.16	0.44	0.16	**5.8**
Eutrophication potential, EP[1)]	kg N eq	1.41	2.7E-02	1.6E-01	**1.6**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	3.2E-04	0.0E+00	1.3E-06	**3.3E-04**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	34,139	479	1,312	**35,930**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	288.5	0.0	38.3	**326.8**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	0	0	0	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	34,867	484	1,443	**36,795**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	0	0	0	**0**
Secondary materials, SM[5)]	kg	0	0	0	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	0	0	0	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	0	0	0	**0**
Recovered energy, RE[8)]	MJ LHV	0	0	0	**0**
Consumption of freshwater, FW[9)]	m^3	0.55	0	0.85	**1.4**
Hazardous waste disposed, HWD[10)]	kg	0	0	0	**0**
Non-hazardous waste disposed, NHWD[11)]	kg	1.7	0	1.6	**3.3**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	5.2E-07	0	8.0E-08	**6.0E-07**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	1.6E-05	0	1.1E-06	**1.7E-05**
Components for re-use, CRU[14)]	kg	0	0	0	**0**
Materials for recycling, MR[15)]	kg	0	0	0	**0**
Materials for energy recovery, MER[16)]	kg	0	0	0	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	0	0	0	**0**

Table 29 Cradle-to-gate production stage (A1-A3) LCA results – 1,000 kg of MUF resin (100% solids)

Impact category and inventory indicators	Unit	A1	A2	A3	Total
Global warming potential, GWP 100[1)]	kg CO_2 eq	1,396	22.9	98.9	**1,518**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	3.0E-04	3.6E-06	1.2E-05	**3.2E-04**
Smog formation potential, SFP[1)]	kg O_3 eq	62.9	8.7	2.8	**74.3**
Acidification potential, AP[1)]	kg SO_2 eq	5.22	0.29	0.15	**5.7**
Eutrophication potential, EP[1)]	kg N eq	1.43	1.7E-02	1.6E-01	**1.6**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	3.3E-04	6.3E-07	1.2E-06	**3.3E-04**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	33,990	320	1,331	**35,641**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	295.3	0.3	37.6	**333.2**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	0	0	0	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	34,736	321	1,460	**36,518**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	0	0	0	**0**
Secondary materials, SM[5)]	kg	0	0	0	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	0	0	0	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	0	0	0	**0**
Recovered energy, RE[8)]	MJ LHV	0	0	0	**0**
Consumption of freshwater, FW[9)]	m^3	0.53	0	0.88	**1.4**
Hazardous waste disposed, HWD[10)]	kg	0	0	0	**0**
Non-hazardous waste disposed, NHWD[11)]	kg	1.7	0	3.1	**4.7**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	5.3E-07	0	7.8E-08	**6.1E-07**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	1.6E-05	0	9.6E-07	**1.9E-05**
Components for re-use, CRU[14)]	kg	0	0	0	**0**
Materials for recycling, MR[15)]	kg	0	0	0	**0**
Materials for energy recovery, MER[16)]	kg	0	0	0	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	0	0	0	**0**

Table 30 Cradle-to-gate Production stage (A1-A3) LCA results – 1,000 kg of MF resin (100% solids)

Impact category and inventory indicators	Unit	A1	A2	A3	Total
Global warming potential, GWP 100[1)]	kg CO_2 eq	5,116	51.0	107.5	**5,275**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	4.2E-04	3.1E-06	1.2E-05	**4.3E-04**
Smog formation potential, SFP[1)]	kg O_3 eq	241.4	17.5	2.3	**261.2**
Acidification potential, AP[1)]	kg SO_2 eq	24.12	0.64	0.17	**24.9**
Eutrophication potential, EP[1)]	kg N eq	9.85	3.8E-02	2.4E-01	**10.1**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	9.4E-04	5.4E-07	1.8E-06	**9.4E-04**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	77,243	720	1,424	**79,386**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	1,261.9	0.2	57.6	**1,319.7**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	0	0	0	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	78,518	726	1,622	**80,866**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	0	0	0	**0**
Secondary materials, SM[5)]	kg	0	0	0	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	0	0	0	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	0	0	0	**0**
Recovered energy, RE[8)]	MJ LHV	0	0	0	**0**
Consumption of freshwater, FW[9)]	m^3	0.41	0	0.84	**1.3**
Hazardous waste disposed, HWD[10)]	kg	0	0	0	**0**
Non-hazardous waste disposed, NHWD[11)]	kg	1.2	0	1.2	**2.4**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	9.7E-07	0	1.2E-07	**1.1E-06**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	4.8E-05	0	1.5E-06	**5.1E-05**
Components for re-use, CRU[14)]	kg	0	0	0	**0**
Materials for recycling, MR[15)]	kg	0	0	0	**0**
Materials for energy recovery, MER[16)]	kg	0	0	0	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	0	0	0	**0**

Table 31 Cradle-to-gate production stage (A1-A3) LCA results – 1,000 kg of PF resin (100% solids)

Impact category and inventory indicators	Unit	A1	A2	A3	Total
Global warming potential, GWP 100[1)]	kg CO_2 eq	2,395	71.9	114.9	**2,582**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	3.0E-04	2.2E-06	1.4E-05	**3.2E-04**
Smog formation potential, SFP[1)]	kg O_3 eq	126.4	24.9	3.5	**154.8**
Acidification potential, AP[1)]	kg SO_2 eq	8.05	0.93	0.17	**9.1**
Eutrophication potential, EP[1)]	kg N eq	5.60	5.6E-02	1.7E-01	**5.8**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	1.2E-04	3.8E-07	1.3E-06	**1.2E-04**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	60,472	1,019	1,551	**63,042**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	1,083.6	0.2	39.6	**1,123.3**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	0	0	0	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	63,718	1,029	1,687	**66,435**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	0	0	0	**0**
Secondary materials, SM[5)]	kg	0	0	0	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	0	0	0	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	0	0	0	**0**
Recovered energy, RE[8)]	MJ LHV	0	0	0	**0**
Consumption of freshwater, FW[9)]	m^3	0.54	0	1.28	**1.8**
Hazardous waste disposed, HWD[10)]	kg	0	0	0	**0**
Non-hazardous waste disposed, NHWD[11)]	kg	1.7	0	3.9	**5.6**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	1.8E-06	0	8.2E-08	**1.9E-06**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	2.3E-05	0	1.0E-06	**2.5E-05**
Components for re-use, CRU[14)]	kg	0	0	0	**0**
Materials for recycling, MR[15)]	kg	0	0	0	**0**
Materials for energy recovery, MER[16)]	kg	0	0	0	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	0	0	0	**0**

Table 32 Cradle-to-gate production stage (A1-A3) LCA results – 1,000 kg of PRF resin (100% solids)

Impact category and inventory indicators	**Unit**	**A1**	**A2**	**A3**	**Total**
Global warming potential, GWP 100[1)]	kg CO_2 eq	2,296	285.8	125.8	**2,708**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	2.3E-04	6.4E-06	1.5E-05	**2.5E-04**
Smog formation potential, SFP[1)]	kg O_3 eq	123.9	98.6	2.8	**225.2**
Acidification potential, AP[1)]	kg SO_2 eq	9.02	3.72	0.18	**12.9**
Eutrophication potential, EP[1)]	kg N eq	6.16	2.2E-01	1.8E-01	**6.6**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	5.3E-03	1.1E-06	1.4E-06	**5.3E-03**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	57,058	4,055	1,716	**62,829**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	1,184.0	0.5	43.0	**1,227.4**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	0	0	0	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	60,323	4,097	1,864	**66,284**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	0	0	0	**0**
Secondary materials, SM[5)]	kg	0	0	0	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	0	0	0	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	0	0	0	**0**
Recovered energy, RE[8)]	MJ LHV	0	0	0	**0**
Consumption of freshwater, FW[9)]	m^3	0.19	0	1.37	**1.6**
Hazardous waste disposed, HWD[10)]	kg	0	0	0	**0**
Non-hazardous waste disposed, NHWD[11)]	kg	0.6	0	1.2	**1.8**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	1.8E-06	0	8.9E-08	**1.9E-06**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	2.3E-05	0	1.1E-06	**2.6E-05**
Components for re-use, CRU[14)]	kg	0	0	0	**0**
Materials for recycling, MR[15)]	kg	0	0	0	**0**
Materials for energy recovery, MER[16)]	kg	0	0	0	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	0	0	0	**0**

Table 33 Cradle-to-gate production stage (A1-A3) LCA results – 1,000 kg of EPI and PEP resins (100% solids)

Impact category and inventory indicators	Unit	EPI resin Total (A1 to A3)	PEP resin Total (A1 to A3)
Global warming potential, GWP 100[1)]	kg CO_2 eq	**2,005**	**2,964**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	**2.0E-03**	**4.3E-03**
Smog formation potential, SFP[1)]	kg O_3 eq	**139.4**	**155.2**
Acidification potential, AP[1)]	kg SO_2 eq	**9.5**	**13.3**
Eutrophication potential, EP[1)]	kg N eq	**3.3**	**3.7**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	**1.2E-03**	**4.2E-04**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	**37,742**	**61,398**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	**1,015.6**	**1,893.1**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	**0**	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	**39,875**	**66,515**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	**0**	**0**
Secondary materials, SM[5)]	kg	**0**	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	**0**	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	**0**	**0**
Recovered energy, RE[8)]	MJ LHV	**0**	**0**
Consumption of freshwater, FW[9)]	m^3	**0.6**	**0.2**
Hazardous waste disposed, HWD[10)]	kg	**2**	**4**
Non-hazardous waste disposed, NHWD[11)]	kg	**18.1**	**33.1**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	**1.2E-06**	**6.8E-07**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	**4.5E-05**	**2.7E-05**
Components for re-use, CRU[14)]	kg	**0**	**0**
Materials for recycling, MR[15)]	kg	**0**	**0**
Materials for energy recovery, MER[16)]	kg	**0**	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	**0**	**0**

Table 34 Cradle-to-gate Production stage (A1-A3) LCA results – 1,000 kg of formaldehyde (100% solids)

Impact category and inventory indicators	Unit	A1	A2	A3	Total
Global warming potential, GWP 100[1)]	kg CO_2 eq	1,160	29.8	69.6	**1,259**
Ozone depletion potential, ODP[1)]	kg CFC-11 eq	3.2E-04	4.0E-06	3.9E-06	**3.3E-04**
Smog formation potential, SFP[1)]	kg O_3 eq	54.3	11.1	4.3	**69.7**
Acidification potential, AP[1)]	kg SO_2 eq	3.56	0.37	0.25	**4.2**
Eutrophication potential, EP[1)]	kg N eq	1.19	2.3E-02	4.3E-01	**1.6**
Abiotic depletion potential, elements ADPelements[2)]	kg Sb eq	8.3E-06	7.0E-07	3.2E-06	**1.2E-05**
Abiotic depletion potential, fossil ADPf[2)]	MJ LHV	34,351	417	753	**35,521**
Renewable primary resources used as an energy carrier (fuel), RPR_E	MJ LHV	270.4	0.3	103.7	**374.4**
Renewable primary resources with energy content used as material, RPR_M[3)]	MJ LHV	0	0	0	**0**
Non-renewable primary resources used as an energy carrier (fuel), $NRPR_E$	MJ LHV	35,256	419	1,110	**36,785**
Non-renewable primary resources with energy content used as material, $NRPR_M$[4)]	MJ LHV	0	0	0	**0**
Secondary materials, SM[5)]	kg	0	0	0	**0**
Renewable secondary fuels, RSF[6)]	MJ LHV	0	0	0	**0**
Non-renewable secondary fuels, NRSF[7)]	MJ LHV	0	0	0	**0**
Recovered energy, RE[8)]	MJ LHV	0	0	0	**0**
Consumption of freshwater, FW[9)]	m^3	0.45	0	0.89	**1.3**
Hazardous waste disposed, HWD[10)]	kg	0	0	0	**0**
Non-hazardous waste disposed, NHWD[11)]	kg	0.0	0	4.3	**4.3**
High-level radioactive waste, conditioned, to final repository, HLRW[12)]	m^3	5.5E-07	0	2.2E-07	**7.7E-07**
Intermediate- and low-level radioactive waste, conditioned, to final repository, ILLRW[13)]	m^3	7.5E-06	0	2.6E-06	**1.1E-05**
Components for re-use, CRU[14)]	kg	0	0	0	**0**
Materials for recycling, MR[15)]	kg	0	0	0	**0**
Materials for energy recovery, MER[16)]	kg	0	0	0	**0**
Recovered energy exported from the product system, EE[17)]	MJ LHV	0	0	0	**0**

Notes to Tables 28 to 34:

1) Calculated as per U.S EPA TRACI 2.1, v1.05, SimaPro v 9.2.0.2 [10].
GWP-100, excludes biogenic CO_2 removals and emissions associated with any biobased products; 100-year time horizon GWP factors are provided by the IPCC 2013 Fifth Assessment Report (AR5). There is no biogenic content in the declared products.

2) Calculated as per CML-IA Baseline V3.05, SimaPro v 9.2.0.2 [10].

3) Calculated as per ACLCA ISO 21930 Guidance [32], 6.2 *Renewable primary resources with energy content used as a material,* RPR_M. N/A for this product system.

4) Calculated as per ACLCA ISO 21930 Guidance [32], 6.4 *Non-renewable primary resources with energy content used as a material,* $NRPR_M$. The LCA software does not allow distinguishing the primary energy used as raw material or as energy carrier. Because the chemical product systems are highly complicated systems and no PCR is available for wood resins, manually estimated values of $NRPR_M$ would be highly uncertain. For that reason, the $NRPR_E$ presents the total NRPR ($NRPR_E$ + $NRPR_M$).

5) Calculated as per ACLCA ISO 21930 Guidance [32], 6.5 Secondary materials, SM; N/A for this product system.

6) Calculated as per ACLCA ISO 21930 Guidance [32], 6.6 *Renewable secondary fuels, RSF*. N/A for this product system.

7) Calculated as per ACLCA ISO 21930 Guidance [32], 6.7 *Non-renewable secondary fuels, NRSF*. N/A for this product system.

8) Calculated as per ACLCA ISO 21930 Guidance [32], 6.8 *Recovered energy, RE*. N/A for this product system.

9) Calculated as per ACLCA ISO 21930 Guidance [32], 9 *Inventory indicators describing consumption of freshwater*. It's calculated from 2019 industry primary data for consumption of freshwater based solely on the foreground system (wood resins manufacturing process).

10) Calculated as per ACLCA ISO 21930 Guidance [32], 10.1 *Hazardous waste disposed*. It's calculated from 2019 industry primary data for hazardous waste disposed based solely on the foreground system (wood resins manufacturing process).

11) Calculated as per ACLCA ISO 21930 Guidance [32], 10.2 *Non-hazardous waste disposed*. It's calculated from 2019 industry primary data for non-hazardous waste disposed based solely on the foreground system (wood resins manufacturing process).

12) Calculated as per ACLCA ISO 21930 Guidance [32], 10.3 *High-level radioactive waste, conditioned, to final repository*. It should be noted that the foreground system (wood resins manufacturing process) does not generate any HLRW. High-level radioactive waste, e.g., when generated by electricity production, consists mostly of spent fuel from reactors." (ISO 21930:2017, clause 7.2.14).

13) Calculated as per ACLCA ISO 21930 Guidance [32], 10.4 *Intermediate- and low-level radioactive waste, conditioned, to final repository*. It should be noted that the foreground system (wood resins manufacturing process) does not generate any ILLRW. Low- and intermediate-level radioactive wastes, e.g., when generated by electricity production, arise mainly from routine facility maintenance and operations (ISO 21930:2017, clause 7.2.14).

14) Calculated as per ACLCA ISO 21930 Guidance [32], 10.5 *Components for re-use*. N/A for this product system.

15) Calculated as per ACLCA ISO 21930 Guidance [32], 10.6 *Materials for recycling*, i.e. secondary material used in the next product system. N/A for this product system.

16) Calculated as per ACLCA ISO 21930 Guidance [32], 10.7 *Materials for energy recovery*, i.e. secondary fuels used in the next product system. N/A for this product system.

17) Calculated as per ACLCA ISO 21930 Guidance [32], 10.8 *Recovered energy exported from the system*. N/A for this product system.

12 Interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are brought together and significant issues are identified and considered in the context of the study goal and scope [2]. In addition, the study's completeness, consistency of all applied information, and sensitivity to key assumptions or parameters as they relate to the goal and scope of the study are evaluated. Lastly, the interpretation phase ends by drawing conclusions, stating the study's limitations, and making recommendations [3].

12.1 Identification of the Significant Issues

ISO 14044 recommends several possible methods to identify significant issues in an LCA study. Based on established LCA practices, the following analytical techniques were applied for the interpretation phase of this LCA study [3]:

- Contribution Analysis, in which the contribution of information modules and processes to the cradle-to-gate LCA results are examined.
- Dominance Analysis, in which significant contributions are examined.

Figures 4 to 9 present a percent contribution analysis by information module for the impact assessment and energy indicator results for amino and phenolic resins and the precursor (formaldehyde). For EPI and PEP, LCA results are only presented for the total (A1 to A3) as manufacturers consider this information proprietary.

Figure 4 shows a contribution analysis of key LCIA and energy use metrics in the production of 1,000 kg of formaldehyde by information module. Formaldehyde manufacture is almost 100% fossil fuel based. Further, most of the environmental burdens associated with the production of formaldehyde can be traced to upstream production of methanol (A1); accounting for upwards 91% of GWP-100. As formaldehyde is a key component in all amino and phenolic wood resins of interest, this upstream burden commonly resonates through the results for the formaldehyde-based resins as well. For example, Figure 5 presents the impact assessment and energy indicator results for 1,000 kg of UF resin. As is evident, module A1 accounts for between 96% (ODP) and 81% (SFP) of the potential environmental impacts. Module A1 also accounts for 95% of the non-renewable energy use and 91% of the GWP-100 in the production of UF resin. Except for SFP (15%) and AP (8%), module A2 is a minor contributor to the overall cradle-to-gate environmental burdens of UF production. Module A3 accounts for less than 12% of the overall potential impacts.

Across all the amino and phenolic resins of interest, Modu*le A1 Extraction and upstream material input production* contributes the largest share of the LCIA category and energy indicator results – accounting for between 55% (smog) and 97% (GWP-100) of the potential environmental burdens. *Module A2 Transportation* contributed 7% to 44% and 3% to 29% of the smog related and acidification emissions, respectively, but was otherwise, a minor contributor (<10%) to the overall manufacturing impact. *Module A3 Manufacturing* contributed 4% to 12% and 2% to 10% to renewable primary energy and eutrophication, respectively, but was otherwise the third largest contributor (<7%) to the overall potential environmental impacts of the specified resins. These LCA results align well with those reported by Wilson 2009 – see Tables 2.9, 3.9, 4.9 and 5.9 [1].

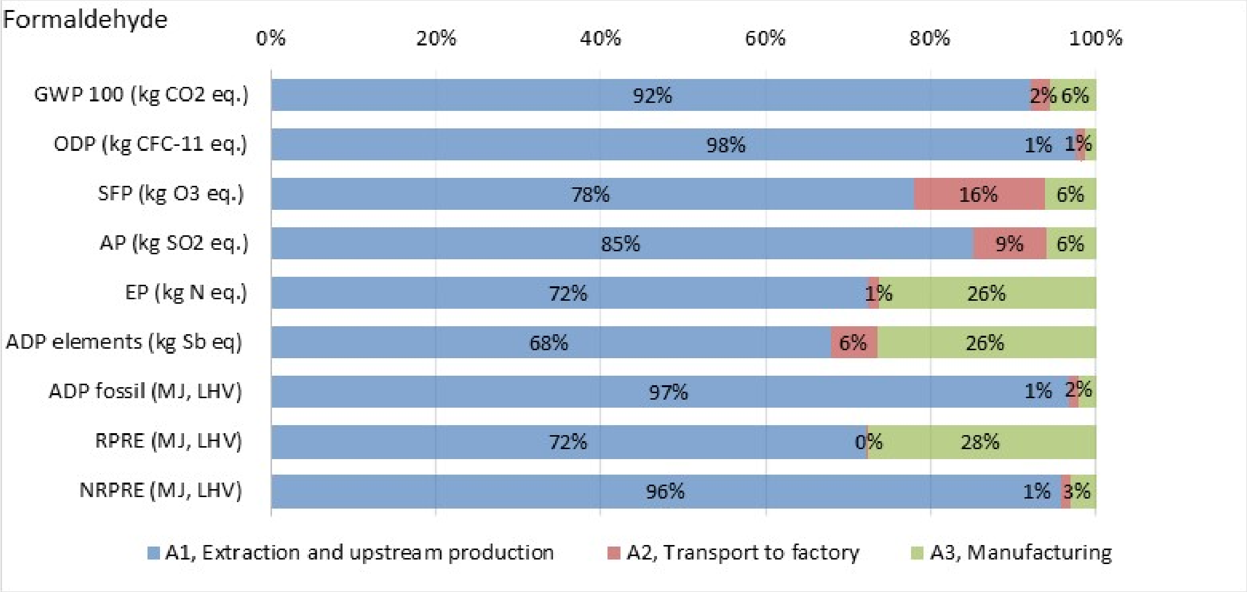

Figure 4 Impact assessment and energy indicator results by stage – 1,000 kg of formaldehyde

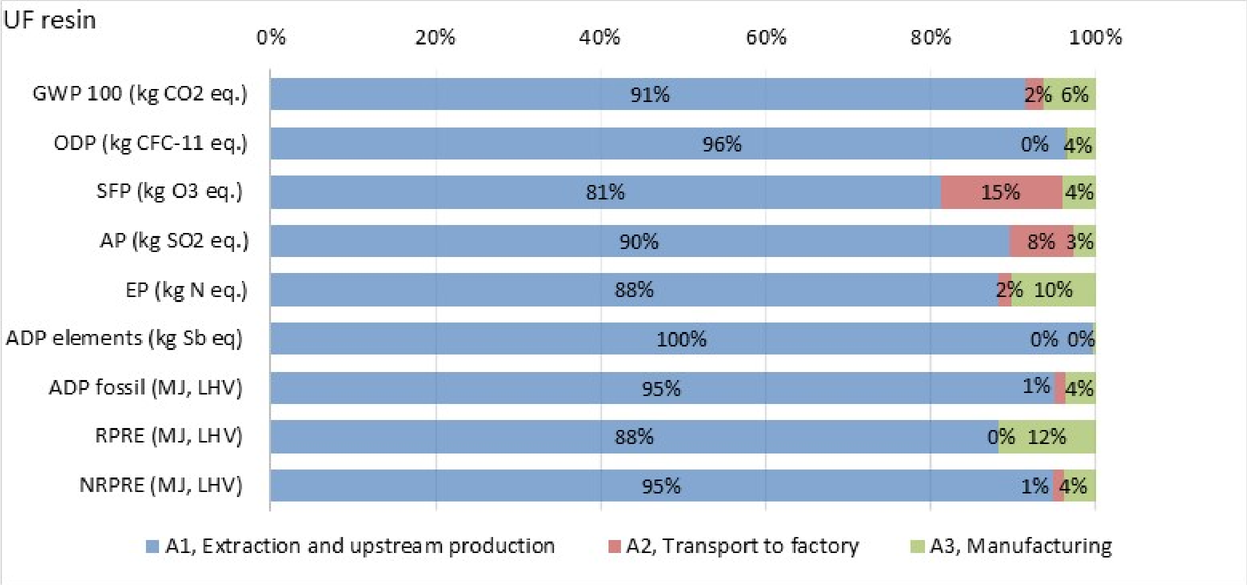

Figure 5 Impact assessment and energy indicator results by stage – 1,000 kg of UF resin

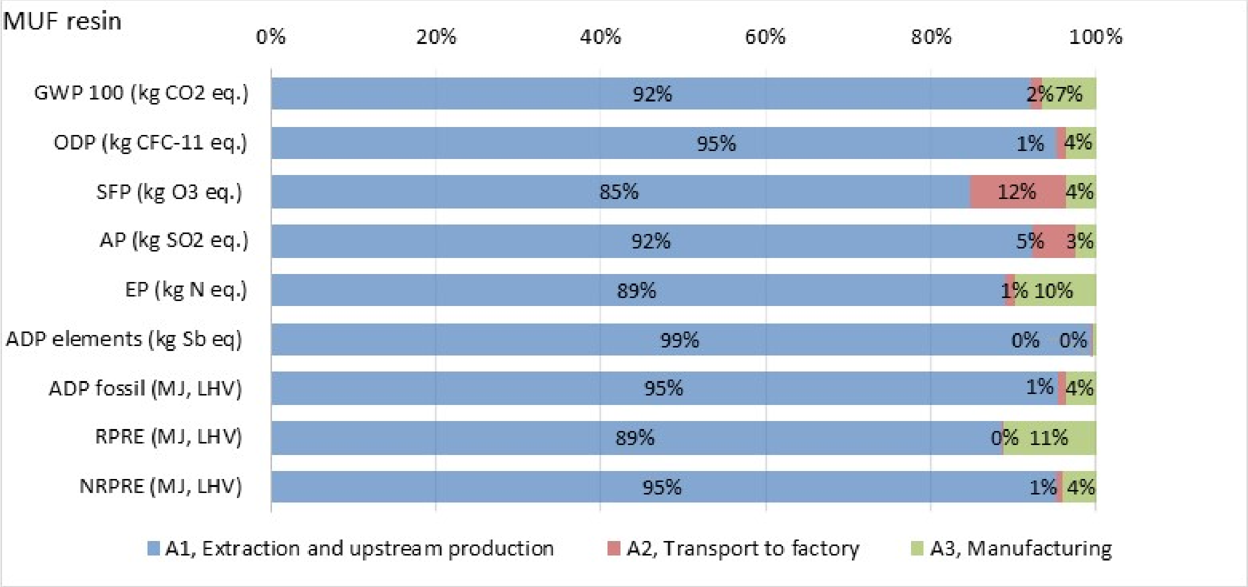

Figure 6 *Impact assessment and energy indicator results by stage – 1,000 kg of MUF resin*

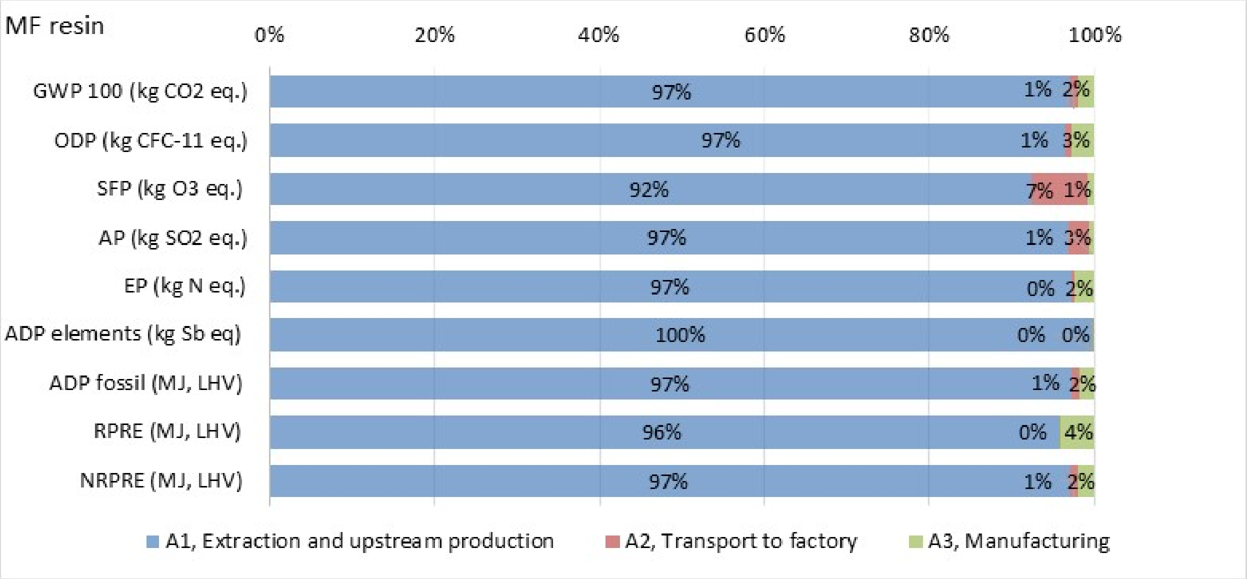

Figure 7 *Impact assessment and energy indicator results by stage – 1,000 kg of MF resin*

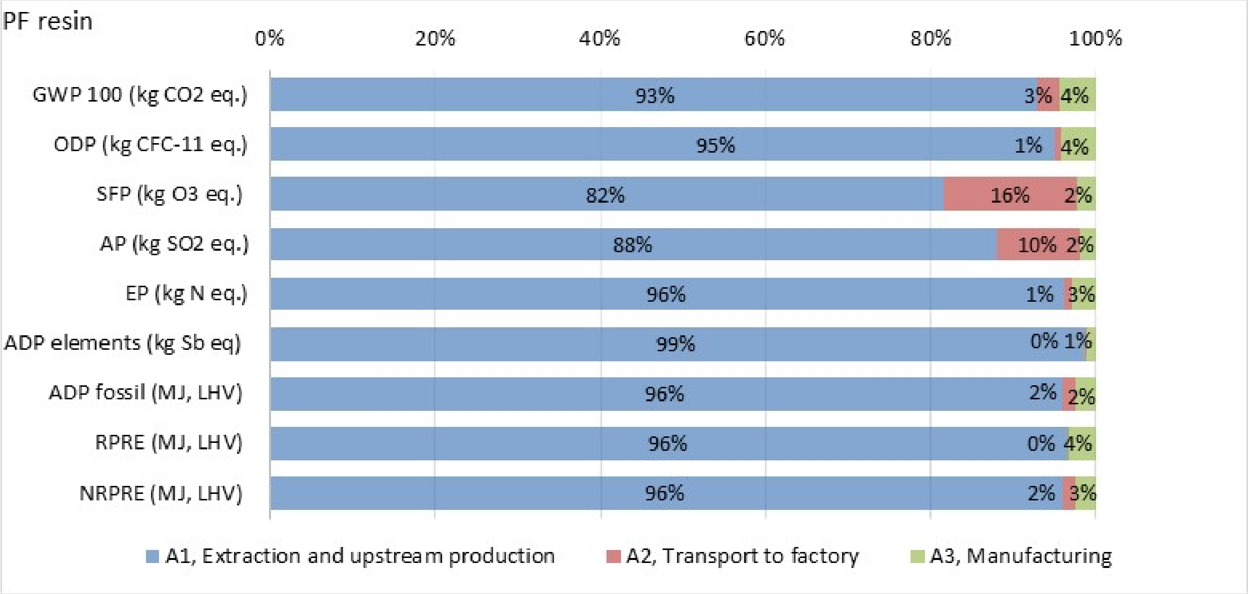

Figure 8 Impact assessment and energy indicator results by stage – 1,000 kg of PF resin

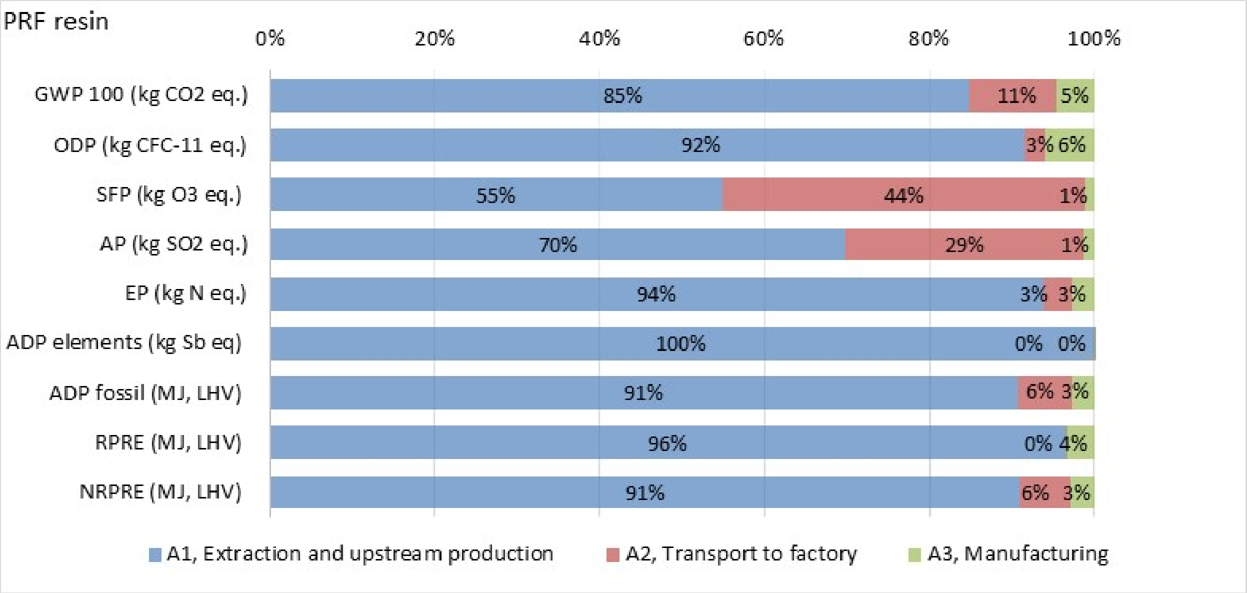

Figure 9 Impact assessment and energy indicator results by stage – 1,000 kg of PRF resin

Given the importance of the cradle-to gate GWP-100 results, a process contribution analysis was conducted to examine the contribution of individual cradle-to-gate processes to the Production stage GWP-100 (in kg CO2 eq.) of 1,000 kg of resins. Tables 35 to 40 show that the top four contributors of the amino and phenolic wood resin products are, in descending order, input chemicals (86% to 97%), on-site natural gas consumption (1% to 7%) and transportation of chemicals (2% to 10%). Similar results can be expected for the non-renewable primary energy indicator.

Table 35 Top 4 significant processes contributing to cradle-to-gate production stage (A1-A3), GWP-100 results – 1,000 kg of formaldehyde (100% solids)

Production stage (A1 to A3)	Formaldehyde	
	kg CO_2 eq.	%
Methanol production, A1	1,160	92%
Electricity production and transmission, A3	68	5%
Transport, freight train, A2	17	1%
Transport, combination truck, long-haul, diesel, A2	13	1%
Rest of processes, A1 to A3	2	0%
Total	**1,259**	**100%**

Table 36 Top 4 significant processes contributing to cradle-to-gate production stage (A1-A3), GWP-100 results – 1,000 kg of UF resin (100% solids)

Production stage (A1 to A3)	UF resin	
	kg CO_2 eq.	%
Urea production, A1	885	58%
Formaldehyde production, A1	511	33%
Natural gas precombustion and combustion, A3	71	5%
Transport, combination truck, long-haul, diesel, A2	33	2%
Rest of processes, A1 to A3	29	2%
Total	**1,530**	**100%**

Table 37 Top 4 significant processes contributing to cradle-to-gate production stage (A1-A3), GWP-100 results – 1,000 kg of MUF resin (100% solids)

Production stage (A1 to A3)	MUF resin	
	kg CO_2 eq.	%
Urea production, A1	788	52%
Formaldehyde production, A1	492	32%
Melamine production, A1	89	6%
Natural gas precombustion and combustion, A3	74	5%
Rest of processes, A1 to A3	76	5%
Total	**1,518**	**100%**

Table 38 Top 4 significant processes contributing to cradle-to-gate production stage (A1-A3), GWP-100 results – 1,000 kg of MF resin (100% solids)

Production Stage (A1 to A3)	MF resin	
	kg CO_2 eq.	%
Melamine production, A1	4,660	88%
Formaldehyde production, A1	347	7%
Methanol production, A1	109	2%
Natural gas precombustion and combustion, A3	71	1%
Rest of processes, A1 to A3	88	2%
Total	**5,275**	**100%**

Table 39 Top 4 significant processes contributing to cradle-to-gate production stage (A1-A3), GWP-100 results – 1,000 kg of PF resin (100% solids)

Production stage (A1 to A3)	PF resin	
	kg CO_2 eq.	%
Phenol production, A1	1,721	67%
Formaldehyde production, A1	500	19%
Sodium hydroxide, production, A1	95	4%
Natural gas precombustion and combustion, A3	88	3%
Rest of processes, A1 to A3	177	7%
Total	**2,582**	**100%**

Table 40 Top 4 significant processes contributing to cradle-to-gate production stage (A1-A3), GWP-100 results – 1,000 kg of PRF resin (100% solids)

Production Stage (A1 to A3)	PRF resin	
	kg CO_2 eq.	%
Phenol production, A1	1,687	62%
Resorcinol production, A1	390	14%
Transport, combination truck, long-haul, diesel, A2	259	10%
Formaldehyde production, A1	182	7%
Rest of processes, A1 to A3	191	7%
Total	**2,708**	**100%**

12.2 Completeness, Consistency, and Sensitivity Check

Evaluating the study's completeness, consistency and sensitivity helps to establish and enhance confidence in, and the reliability of, the results of the LCA study, including the significant issues identified in the first element of the interpretation [3].

The objective of the completeness check is to ensure that all relevant information and data needed for the interpretation are available and complete [3]. All wood resin data were checked for data completeness. All input and output data were found to be complete, and no gaps were identified at information modules A1 to A3 (see Sections 4 to 10, Annex A).

Through a rigorous process, consistency was ensured between all wood resin systems in terms of calculation rules, methods, models, and data quality, including data source, time-related coverage, technology, and geographical coverage (see Section 3.5, Sections 4 to 10, and Annex A). Table 2 summarizes the data quality assessment conducted in the framework of this LCA study.

To assess how factors such as uncertainties in data, and assumptions would affect the reliability of the results and conclusions, a sensitivity check was conducted. The sensitivity check includes the results of the sensitivity analysis and uncertainty analysis [3].

The sensitivity analysis procedure is a comparison of the LCA results obtained using certain given assumptions, methods, or data, with the LCA results obtained using altered assumptions, methods, or data [2]. ISO 14044 Clause B.3.3 states: "Sensitivity can be expressed as the percentage of change or as the absolute deviation of the results. On this basis, significant changes in the results (e.g., larger than 10%) can be identified" [3].

In this study, a key methodological choice was the application of a parameterized mass allocation method across multi-product formaldehyde-based resin systems to better partition (seperate) the LCI data for the production of formaldehyde (precursor) from the resin production data instead of applying a default mass allocation method based solely on the total production quantities.

Scenario analysis was conducted to illustrate the impact of comparing the applied parametrized approach results (base case) with a default mass allocation approach (scenario case) for formaldehyde and resins-see Table 41. The scenario analysis results are presented in detail in Annex C.1, Tables C.1.1 to C.1.6. The positive (+) or negative (-) signs of deviation (in %) depend on the mathematical signs (+/-) of both the value of base case and the deviation of the LCIA and energy indicators. For example, the influence of this scenario to GWP-100 of formaldehyde compared to the base case is negative (-2.2%); indicating a 2.2% higher GWP-100 compared to the base case. *The influence of replacing the parametrized mass allocation with the default mass allocation approach on the GWP-100 and $NRPR_E$ indicators is an* <u>*insignificant*</u> *change of less than 1% for all five (5) amino and phenolic resins.*

In summary, the scenario analysis indicates that replacing parametrized mass allocation with default mass allocation approach had an insignificant influence on the LCA results (in general, less than 5% change) for all LCIA and inventory indicators for all five (5) of amino and phenolic resins.

Table 41 Sensitivity analysis - Mass allocation approach (100%)

Resins and Formaldehyde (CH2O)	**Material and formulation water Inputs**[1]	**All Inputs/ Outputs**[2] [3]
Formaldehyde	PGF	1.0
UF resin	PGF	1.0
MUF resin	PGF	1.0
MF resin	PGF	1.0
PF resin	PGF	1.0
PRF resin	PGF	1.0
Other resins	n/a	1.0
Allocation approach	PGF	Mass allocation

Example:
Electricity consumption factors per resin and formaldehyde (on-site Formox process) are calculated as follows:
Electricity Total Facility = AF*1*X+AUF*1*X+AMUF*1*X+APF*1*X+APRF*1*X+AMF*1*X+A Others*1*X
Where,
A- stands for “annual production per formaldehyde or resin type” per facility.
X- stands for the “variable (in kWh/kg resin)” per facility. If X is equal to 50, then the electricity factors of formaldehyde, UF, MUF, MF, PF, PRF and other resins are 50, 50, 50, 50, 50, 50, and 50, respectively.
Similar formulas are used for all selected input/output flows.

Notes to Table 41:
[1] Plant generic formulations (PGF) are used for material and formulation water inputs- see Sections 4 to 10.
[2] Mass allocation is applied for all inputs/outputs.
[3] Check Table 3 for the baseline parametrized mass allocation approach.

A Monte Carlo uncertainty analysis was also conducted to assess the combined uncertainty effect of the data variability on the GWP-100 results (see Annex C.2, Table C.2).

Based on the industry sample data, [minimum; maximum] range data were calculated per each input/output flow for the resins and formaldehyde production. These data are used in the Monte Carlo uncertainty analysis. This uncertainty analysis assesses the combined uncertainty effect of the inventory data (both foreground and background)- see Sections 4 to 10 and Annex B. It should be noted that U.S. EPA TRACI version 2.1 methodology and CML-baseline version 4.7 methodology, have not specified any uncertainty information of the characterization factors per impact category.

As a statistical method, Monte Carlo analysis is used to establish the uncertainty range, which expresses the variance between the upper and lower confidence limit [97.5%, 2.5%], in the calculated LCA results. Based on 1,000 runs, such information provides a quantitative indication of the range of GWP-100 results for the specified resin product.

12.3 Conclusions, Limitations and Recommendations

Based on the goal and scope of this LCA, life cycle inventory, impact assessment, and interpretation phases, the following conclusions can be reached:

- For formaldehyde-based wood resins, the input of formaldehyde drives the LCIA and resource use metrics. All these resins are derived from fossil fuels – either as a material or as an energy input. As methanol (CH3OH), the simplest alcohol, is the key input in the manufacture of formaldehyde its environmental profile is equally key to the environmental profile of these wood resins.
- For the water-based polymer resins EPI and PEP, the amount of EPI-water-based polymer emulsion and PEP-polyurethane emulsion cross-linker, respectively, typically drives the potential environmental burden.
- Natural gas consumption followed by electricity use generally dictates the impact of Module A3 – wood resin manufacturing. However, module A3 typically accounts for less than 10% of the overall impact of resin production.

A key modelling element of the study was the necessity to apply a parametrized mass allocation approach across multi-product formaldehyde-based resin systems to better partition (separate) the LCI data for the production of formaldehyde (precursor) from the resin production data instead of applying a default mass allocation method based solely on the total production quantities. The scenario analysis indicated that replacing parametrized mass allocation with default mass allocation approach would *insignificantly* influence the LCA results (less than 5% change) for the LCIA and energy indicators for all five (5) of amino and phenolic resins. The reason for that is that resin manufacturing (module A3) is not a significant contributor and typically accounts for less than 10% of the overall impact of resin production.While the parametrized mass allocation approach leads to technically sound LCI data for formaldehyde production and amino and phenolic resins, “batchwise” production data, that where not available by the surveyed plants, would have been the best possible approach (no parametrized partition required).

It is recommended that in the future more effort needs to go into having greater wood resin manufacture participation and LCI data collection, perhaps on a “batchwise” production basis, to better delineate inputs and outputs.

Finally, “*LCA addresses potential environmental impacts and does not predict absolute or precise environmental impacts due to (a) the relative expression of potential environmental impacts to a reference unit, (b) the integration of environmental data over space and time, (c) the inherent uncertainty in modeling of environmental impacts, and (d) the fact that some possible environmental impacts are clearly future impacts” [3].*

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Annex A Benchmarked LCI data for the Production of Formaldehyde and Wood Resins

Table A.1 Molar ratio check for amino and phenolic wood resins

Amount	**Unit**	**Resins**	**Molar Ratio1)**			**Expected molar ratio range for commercial resins for use in wood industry**	**Source**
			Wilson 2009 2) [1]	ecoinvent 3.7.1 2021 2) [21], [23], [26], [11]	Athena 2022 6)		
1	kg	UF3)	1.1	1.7	1.1	1.1 to 1.8	Dunky, M., Pizzi, A., 2002 [17]
1	kg	MUF	1.2	1.2	1.1	1.1 to 1.3	Wilson 2009 [1]
1	kg	MF4)	n/a	1.7	1.6	1.5 to 2.0	Frihart, Ch. R. 2013 [24]
						Around or above 2.0	Li, T., et.al. 2018 [25]
1	kg	PF5)	2.2	n/a	2.2	2.0 to 2.5	Wilson 2009 [1]
						1.0 to 3.0	Frihart, Ch. R. 2013 [24]
1	kg	PRF5)	0.61	n/a	0.54	< 1.0	Wilson 2009 [1]
						0.5 to 0.8	Frihart, Ch. R. 2013 [24]

Notes to Table A.1:

1) Molar ratio is dimensionless quantity.

2) Check Tables A.4.2, A.5.2, A.6.2, A.7.2, and A.8.2 for details.

3) "*The higher the F/U molar ratio, the higher is the content of free formaldehyde in the resin. Assuming stable conditions in the resins, that means that post-added urea has had enough time to react with the resin, and the content of free formaldehyde is very similar even for different cooking procedures. In a coarse scale, the content of free formaldehyde in a straight UF-resin is approx. 0.1% at F/U = 1.1 and 1 % at F/U = 1.8. It also decreases with time due to ageing reactions and to the free formaldehyde reacting further*" [17].

4) "*In normal applications, the formaldehyde to melamine ratio is about 1.5-2*" [24]. "In typical MF synthesis, the formaldehyde to melamine ratio (F/M) is generally around or above 2.0. MF molar range: > 1.00 and <3.0 [25].

5) "*For all PF adhesives, phenol is reacted with formaldehyde or a formaldehyde precursor under the proper conditions to produce an oligomer that can undergo further polymerization during the setting process. There are two basic types of oligomers, novolaks that have a formaldehyde/phenol (F/P) ratio of less than 1 and are generally made under acidic conditions, and resole resins made under basic conditions with F/P ratios of greater than 1.*
Novolak resins are made using acidic conditions with typical formaldehyde to phenol ratios of 0.5-0.8 at a pH of 1-4. On the other hand, resole resins are generally made using alkali hydroxides with a formaldehyde to phenol ratio of 1.0-3.0 at a pH of 7-13" [24].

6) "Athena 2022" refers to this LCA report.

Table A.2 Mass balance check for formaldehyde and amino and phenolic wood resins

Amount	Unit	Resins and Formaldehyde	Total input chemicals (no water) in kg/kg 100% solid resins	Total input chemicals (no water) in kg/kg 100% solid resins	Total input chemicals (no water) in kg/kg 100% solid resins
			Wilson 2009 [1][1]	ecoinvent v3.7.1 2021[1] [15], [21], [23], [26], [11]	Athena 2022[4]
1	kg	Formaldehyde	1.2[2]	1.2[3]	1.2
1	kg	UF	1.2	1.1	1.2
1	kg	MUF	1.3	1.3	1.1
1	kg	MF	n/a	1.1	1.1
1	kg	PF	1.1	n/a	1.1
1	kg	PRF	1.0	n/a	1.1

Notes to Table A.2:

[1] Check Tables A.3, A.4.1, A.5.1, A.6.1, A.7.1, and A.8.1 for details.

[2] It takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde [1].

[3] Silver process, 1.185 to 1.226 kg methanol to produce formaldehyde; Formox process, 1.135 to 1.170 kg methanol to produce formaldehyde [11].

[4] "Athena 2022" refers to this LCA report.

Table A.3 Benchmarked LCI data for the production of 1.0 kg of formaldehyde (100% solids)

Inputs/Outputs	Unit	Amount per 1 kg Formaldehyde (100% solids)	Comments	Amount per 1 kg Formaldehyde (100% solids)
		ecoinvent v3.7.1 2021 [15], [11][1]		Wilson 2009 (not available[4])
INPUTS				
Chemicals				
Methanol	kg	1.20[2]		1.20[5]
Total (without water)	kg	1.20		
Water	kg			
Electricity and fuel use				
Electricity, medium voltage	kWh	0.15		
Chemical factory, organics	unit	4.0E-10		
Nitrogen, liquid	kg	0.019[3]		
OUTPUTS				
Formaldehyde	kg	1.00		
By-product/Waste				
Steam, in chemical industry	kg	2.30		
Emissions to air				
Carbon dioxide, fossil	kg	0.11	thermal incineration of off-gases - Silver process only	
Carbon monoxide, fossil	kg	1.0E-04	Silver+ Formox processes	

Inputs/Outputs	**Unit**	**Amount per 1 kg Formaldehyde (100% solids)**	**Comments**	**Amount per 1 kg Formaldehyde (100% solids)**
		ecoinvent v3.7.1 2021 [15], [11]1)		Wilson 2009 (not available4))
Formaldehyde	kg	2.5E-05	Silver+ Formox processes	
Methanol	kg	3.1E-05	Silver+ Formox processes	
Nitrogen	kg	0.0193)		
Nitrogen oxides	kg	3.8E-04	Silver process only	
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	3.0E-06	Silver+ Formox processes	
Particulates, > 2.5 um, and < 10um	kg	5.0E-06	Formox process; Silver process (negligible)	
Waste				
Spent Formox catalyst base from formaldehyde production	kg	0.050	Formox process	

Notes to Table A.3:

1) ecoinvent v3.7.1 2021, eco-Query: oxidation of methanol [15], [11].

2) Formaldehyde is produced industrially by the oxidation/dehydrogenation of methanol (silver catalyst process) or by oxidation of methanol with air (Formox process). This dataset represents an average of these two processes [15], [11].

3) One Nm^3 of nitrogen is equal to 1.2506 kg. Nitrogen is mainly used during the production of chemicals for 'blanketing', which is the process of applying gas to the vapour space of a container or vessel in order to control its composition [15], [11].

4) Wilson 2009 report has not provided the LCI data for the production of formaldehyde [1].

5) It takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde [1].

Table A.4.1 Benchmarked LCI data for the production of 1.0 kg of UF resin (100% solids)

Inputs/Outputs	Unit	Amount per 1 kg UF 65% solids[1)	**Amount per 1 kg UF (100% solids)**[6)	**Amount per 1 kg UF (100% solids)**[8)
		Wilson 2009- with CH2O production burden [1]	Wilson 2009- with CH2O production burden	ecoinvent v3.7.1, 2021 [21]
INPUTS				
Chemicals				
Urea	kg	0.47	0.73	0.59[9)
Formaldehyde	kg			0.49
Methanol[7)	kg	0.31	0.48	
Formic acid	kg	4.7E-05	7.3E-05	
Ammonium sulfate	kg	3.2E-05	4.9E-05	
Sodium hydroxide	kg	2.2E-04	3.4E-04	0.005
Total (without water)	kg	0.78	1.20	1.08
Total (with formulation water)	kg	0.82	1.25	1.11
Water [2)				
Water for producing UF resin	kg	0.033	0.051	0.033
Water use; cooling tower	kg	0.46	0.70	0.46
Water other; boiler makeup	kg	0.0095	0.015	
Electricity and fuel use				
Electricity (Total)	kWh	0.031	0.048	0.026
Electricity	kWh	0.018	0.027	
Electricity for emissions control	kWh	0.014	0.021	
Natural gas	m3	0.0073	0.011	
Heat, total	MJ			1.4
Propane	L	9.4E-06	1.4E-05	
OUTPUTS				
UF liquid resin	kg	1.00	1.00	1.00
Emissions to air[3)				
CO_2 [4), fossil (GHG) [5)	kg	0.016	0.024	
CO [4)	kg	3.4E-05	5.2E-05	
VOC [5)	kg	5.1E-05	7.9E-05	
Particulate	kg	2.3E-06	3.6E-06	
Formaldehyde (HAP) [5)	kg	7.8E-06	1.2E-05	0.0010
Methanol (HAP) [5)	kg	6.1E-06	9.4E-06	
Dimethyl ether	kg	2.2E-05	3.4E-05	
Water (vapour)	kg			0.18
Emissions to water[3)				
BOD	kg	6.2E-04	9.5E-04	
TSS	kg	3.7E-04	5.6E-04	
Solids	kg	2.2E-04	3.4E-04	
Ammonia nitrogen (NH3N)	kg	1.2E-04	1.9E-04	
Formaldehyde (HCHO)	kg	7.3E-05	1.1E-04	
Emissions to land[3)				

Inputs/Outputs	**Unit**	Amount per 1 kg UF 65% solids1)	**Amount per 1 kg UF (100% solids)**6)	**Amount per 1 kg UF (100% solids)**8)
		Wilson 2009- with CH2O production burden [1]	Wilson 2009- <u>with</u> CH2O production burden	ecoinvent v3.7.1, 2021 [21]
Solids	kg	2.2E-04	3.4E-04	
Water	kg			0.31

Notes to Table A.4.1:

1) All chemical weights given at either 100% non-volatile solids or dry except for UF resin given on a 65% solids basis- see Tables 2.3 and 2.5 [1].

2) There is a significant amount of water recycling back into the resin [1].

3) Emissions data reported in survey [1]. BOD and TSS stand for biological oxygen demand and total suspended solids, respectively.

4) CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant [1].

5) GHG, VOC, and HAP stand for greenhouse gas, volatile organic compound, and hazardous air pollutant, respectively [1].

6) Data per 1 kg UF resin (100% solids) are calculated by Athena. To determine the LCI data for a resin 100% solids, divide the UF 65% solids data in this table by the decimal value of its stated use solids percentage (0.65) [1].

7) It takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde [1].

8) ecoinvent v3.7.1 2021, eco-Query: UF resin production [21].

9) The exchange has been updated to 0.59 kg Urea as indicated in Althaus H.-J., et.al, 2007 [1], [21]. The updated value was confirmed per email with ecoinvent on Dec 14, 2021.

Table A.4.2 Benchmarked LCI data - Molar ratio of formaldehyde to urea for UF resin (100% solids)

Inputs	**Molar Mass (g/mol)**	**Wilson 2009 [1]**			**ecoinvent v3.7.1 2021 [21], [11]**		
		Mass (in gram)	**No. of moles**	**Molar ratio**	**Mass (in gram)**	**No. of moles**	**Molar ratio**
Methanol	32.0						
Formaldehyde (F)	30.0	396.2	13.2	**1.1**1) 2)	490.0	16.3	**1.7**1) 2)
Urea (U)	60.1	727.7	12.1		587.7	9.8	

Notes to Table A.4.2:

1) Molar ratio is dimensionless quantity.

2) *“The molar ratio of formaldehyde to urea was used as a check on the quality of the data [1].*

Table A.5.1 Benchmarked LCI data for the production of 1.0 kg of MUF resin (100% solids)

Inputs/Outputs	**Unit**	Amount per 1 kg MUF (60% solids)1)	**Amount per 1 kg MUF (100% solids)6)**	**Amount per 1 kg MUF (60% solids)8)**
		Wilson 2009- with CH2O production burden [1]	Wilson 2009- with CH2O production burden	ecoinvent v3.7.1, 2021 [23]
INPUTS				
Chemicals				
Melamine	kg	0.081	0.13	0.081
Urea9)	kg	0.40	0.66	0.40
Formaldehyde	kg			
Methanol7)	kg	0.30	0.51	0.30
Formic acid	kg	5.1E-05	8.5E-05	5.1E-05
Ammonium sulfate	kg	2.9E-05	4.9E-05	2.9E-05
Sodium hydroxide	kg	2.1E-04	3.5E-04	2.1E-04
Total (without water)	kg	0.78	1.30	0.78
Total (with formulation water)	kg	0.91	1.52	
Water2)				
Water for producing MUF resin	kg	0.13	0.21	
Water use; cooling tower	kg	0.58	0.97	
Water other; boiler makeup water	kg	0.085	0.14	
Water, unspecified natural origin	kg			0.79
Chemical factory, organics	unit			4.0E-10
Electricity and fuel use				
Electricity (Total)	kWh	0.035	0.059	0.035
Electricity	kWh	0.021	0.035	
Electricity emissions control	kWh	0.014	0.024	
Natural gas used in boiler	m3	0.014	0.023	
Heat, from steam, in chemical industry	MJ			0.20
Propane	L	1.6E-05	2.6E-05	1.6E-05
OUTPUTS				
MUF liquid resin	kg	1.00	1.00	1.00
Emissions to air3)				
$CO_2$4), fossil (GHG)5)	kg	0.026	0.043	
CO4)	kg	1.3E-05	2.2E-05	
VOC 5)	kg	4.9E-05	8.2E-05	
Particulate	kg	1.7E-06	2.8E-06	
Formaldehyde (HAP)5)	kg	7.9E-06	1.3E-05	7.9E-06
Methanol (HAP)5)	kg	5.5E-06	9.2E-06	
Dimethyl ether	kg	2.3E-05	3.8E-05	2.3E-05
Emissions to water3)				
BOD	kg	6.6E-04	0.0011	6.6E-05
COD	kg			1.3E-04
TSS	kg	3.9E-04	6.6E-04	
DOC	kg			4.9E-05

Inputs/Outputs	**Unit**	Amount per 1 kg MUF (60% solids)1)	**Amount per 1 kg MUF (100% solids)6)**	**Amount per 1 kg MUF (60% solids)8)**
		Wilson 2009- <u>with CH2O</u> production burden [1]	Wilson 2009- <u>with CH2O</u> production burden	ecoinvent v3.7.1, 2021 [23]
Solids	kg	2.4E-04	4.0E-04	
Ammonia nitrogen	kg	1.3E-04	2.2E-04	
Formaldehyde	kg	7.8E-05	1.3E-04	7.8E-05
Nitrogen	kg			1.3E-04
Solids, inorganic	kg			2.4E-04
Suspended solids, unspecified	kg			3.9E-04
Emissions to land3)				
Solids	kg	5.1E-05	8.5E-05	
Wastewater	kg			0.51

Notes to Table A.5.1:

1) All chemical weights given at either 100% non-volatile solids or dry except for MUF resin given on a 60% solids basis -see Tables 3.3 and 3.5 [1].

2) There is a significant amount of water recycling back into the resin [1].

3) Emissions data reported in survey [1]. BOD, COD, TSS and DOC stand for biological oxygen demand, chemical oxygen demand, total suspended solids, and dissolved organic carbon, respectively.

4) CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant [1].

5) GHG, VOC, and HAP stand for greenhouse gas, volatile organic compound, and hazardous air pollutant, respectively [1].

6) Data per 1 kg MUF 100% solids are calculated by Athena. To determine the LCI data for a resin 100% solids, divide the MUF 60% solids data in this table by the decimal value of its stated use solids percentage (0.60) [1].

7) It takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde [1].

8) ecoinvent v3.7.1 2021, eco-Query: MUF production [23], “*Based on data for MUF adhesive production from six plants in the US, presented in Table 25: "MUF Wilson, process modeled in SimaPro" by Messmer, Annika & Chaudhary, Abhishek. (2015). Life cycle assessment of adhesives used in wood constructions. Master thesis, ETH Zurich*.".

9) ecoinvent v3.7.1 2021 [23], data has been updated to 0.397 kg Urea and 0.30 kg methanol as indicated in the original Wilson 2009 report [1]. The updated value was confirmed per email with ecoinvent on Dec 6, 2021.

Table A.5.2 Benchmarked LCI data - Molar ratio of formaldehyde to urea plus melamine for MUF resin (100% solids)

Inputs	**Molar Mass (g/mol)**	**Wilson 2009 [1]**			**ecoinvent v3.7.1 2021 [23]**		
		Mass (in gram)	**No. of moles**	**Molar ratio**	**Mass (in gram)**	**No. of moles**	**Molar ratio**
Methanol	32.0						
Formaldehyde	30.0	422.2	14.1	**1.2**1) 2)	253.3	8.4	**1.2**1) 2)
Urea	60.1	661.7	11.0		397.0	6.6	
Melamine	126.1	134.7	1.1		80.8	0.6	

Notes to Table A.5.2:

1) Molar ratio is dimensionless quantity.

2) “*The molar ratio of formaldehyde to urea plus melamine was used as a check on the quality of the data [1].*

Table A.6.1 Benchmarked LCI data for the production of 1.0 kg of MF resin (100% solids)

Inputs/Outputs	Unit	Amount per 1 kg MF (100% solids)	Amount per 1 kg MF 100% solids
		ecoinvent v3.7.1 2021 [26] 1)	Wilson 2009 [1] (not available)
INPUTS			
Chemicals			
Melamine	kg	0.77	
Formaldehyde	kg	0.31	
Total (without water)	kg	1.08	
Water			
Electricity and fuel use			
Electricity (Total)	kWh	0.013	
Natural gas	m3	0.033	
Heat, district or industrial, other than natural gas	MJ, HHV	1.45	
OUTPUTS			
MF liquid resin	kg	1	
Emissions to air			
Formaldehyde	kg	0.0010	
Emissions to water -n/a			
Emissions to land - n/a			

Notes to Table A.6.1:
1) ecoinvent v3.7.1 2021, eco-Query: MF resin production [26].

Table A.6.2 Benchmarked LCI data - Molar ratio of formaldehyde to melamine for MF resin (100% solids)

Inputs	Molar Mass (g/mol)	ecoinvent v3.7.1 2021		
		Mass (in gram)	No. of moles	Molar ratio
Methanol	32.0			
Formaldehyde	30.0	310.0	10.3	**1.7** 1) 2)
Melamine	126.1	770.0	6.1	

Notes to Table A.6.2:
1) Molar ratio is dimensionless quantity.
2) The molar ratio of formaldehyde to melamine is used as a check on the quality of the data.

Table A.7.1 Benchmarked LCI data for the production of 1.0 kg of PF resin (100% solids)

Inputs/Outputs	**Unit**	Amount per 1 kg PF (47.4% solids)$^{1)}$	**Amount per 1 kg PF (100% solids)$^{6)}$**	**Amount per 1 kg PF (100% solids)$^{8)}$**
		Wilson 2009- with CH2O production burden [1]	Wilson 2009- with CH2O production burden	ecoinvent v3.7.1, 2021 (not available)
INPUTS				
Chemicals				
Phenol	kg	0.24	0.51	
Methanol[7]	kg	0.21	0.44	
Sodium hydroxide	kg	0.061	0.13	
Total (without water)	kg	0.51	1.08	
Total (with formulation water)	kg	0.81	1.71	
Water$^{2)}$				
Water for producing PF resin	kg	0.30	0.63	
Water use; cooling tower	kg	0.016	0.033	
Water, well source	kg	0.037	0.078	
Water, river	kg			
Electricity and fuel use				
Electricity (Total)	kWh	0.036	0.075	
Electricity	kWh	0.022	0.046	
Electricity for emissions control	kWh	0.014	0.029	
Natural gas	m3	0.0082	0.017	
Propane	L	2.9E-06	6.2E-06	
OUTPUTS				
PF liquid resin	kg	1.00	1.00	
Emissions to air$^{3)}$				
$CO_2$$^{4)}$, fossil (GHG)$^{5)}$	kg	0.018	0.037	
CO$^{4)}$	kg	3.8E-05	8.0E-05	
VOC$^{5)}$	kg	2.9E-05	6.1E-05	
Particulate	kg	2.3E-06	4.9E-06	
Formaldehyde (HAP)$^{5)}$	kg	6.7E-06	1.4E-05	
Methanol (HAP)$^{5)}$	kg	3.2E-06	6.8E-06	
Phenol (HAP)$^{5)}$	kg	2.0E-06	4.3E-06	
Dimethyl ether	kg	4.7E-06	1.0E-05	
Emissions to water$^{3)}$- n/a				
Emissions to land$^{3)}$				
Solids	kg	2.0E-04	4.2E-04	

Notes to Table A.7.1:

$^{1)}$ All chemical weights given at either 100% non-volatile solids or dry except for PF resin given on a 47.5% solids basis -see Tables 4.3 and 5.5 [1].

$^{2)}$ There is a significant amount of water recycling back into the resin [1].

$^{3)}$ Emissions data reported in survey [1].

$^{4)}$ CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant [1].

$^{5)}$ GHG, VOC, and HAP stand for greenhouse gas, volatile organic compound, and hazardous air pollutant, respectively [1].

[6] Data per 1 kg PF 100% solids are calculated by Athena. To determine the LCI data for a resin 100% solids, divide the PF 60% solids data in this table by the decimal value of its stated use solids percentage (0.474) [1].
[7] It takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde [1].
[8] ecoinvent v3.7.1 2021 eco-Query, data are not available for PF resin (resole resins, with F/P ratios of greater than 1). Data are only available for a generic phenol resin (novolac resins, with F/P ratio of 0.5)- see Table A.1.

Table A.7.2 Benchmarked LCI data - Molar ratio of formaldehyde to phenol for PF resin (100% solids)

Inputs	**Molar Mass (g/mol)**	**Wilson 2009 [1]**		
		Mass (in gram)	**No. of moles**	**Molar ratio**
Methanol	32.0			
Formaldehyde	30.0	367.4	12.2	**2.2**[1] [2]
Phenol	94.1	514.8	5.5	

Notes to Table A.7.2:
[1] Molar ratio is dimensionless quantity.
[2] "*The molar ratio of formaldehyde to phenol was used as a check on the quality of the data. [1].*"

Table A.8.1 Benchmarked LCI data for the production of 1.0 kg of PRF resin (100% solids)

Inputs/Outputs	**Unit**	Amount per 1 kg PRF (60% solids)1)	**Amount per 1 kg PRF 100% solids6)**	**Amount per 1 kg PRF (100% solids)8)**
		Wilson 2009- with CH2O production burden [1]	Wilson 2009- with CH2O production burden	ecoinvent v3.7.1, 2021 (not available)
INPUTS				
Chemicals				
Phenol	kg	0.28	0.46	
Resorcinol	kg	0.19	0.32	
Methanol7)	kg	0.10	0.17	
Ethanol	kg	0.0074	0.012	
Sodium hydroxide (50%)	kg	0.0037	0.0062	
Total (without water)	kg	0.58	0.97	
Total (with formulation water)9	kg	0.58	0.97	
Water 2)				
Water, municipal	kg	0.46	0.77	
Water, well source	kg	0.20	0.33	
Electricity and fuel use				
Electricity (Total)	kWh	0.099	0.16	
Electricity	kWh	0.083	0.14	
Electricity for emissions control	kWh	0.016	0.027	
Natural gas	m3	0.032	0.053	
Propane	L	2.5E-05	4.2E-05	
OUTPUTS				
PRF liquid resin	kg	1.00	1.00	
Emissions to air 3)				
CO2 4), fossil (GHG) 5)	kg	0.069	0.11	
CO 4)	kg	1.5E-04	2.5E-04	
VOC 5)	kg	3.4E-05	5.6E-05	
Particulate	kg	3.0E-06	5.0E-06	
Formaldehyde (HAP) 5)	kg	8.8E-06	1.5E-05	
Methanol (HAP) 5)	kg	5.2E-06	8.7E-06	
Phenol (HAP) 5)	kg	4.2E-06	6.9E-06	
Emissions to water				
BOD		0.0028	0.0047	
TSS	kg	1.7E-04	2.8E-04	
Phenol	kg	1.1E-04	1.9E-04	
Formaldehyde	kg	3.3E-04	5.5E-04	
Emissions to land 3)				
Solids	kg	1.7E-04	2.8E-04	

Notes to Table A.8.1:

1) All chemical weights given at either 100% non-volatile solids or dry except for PRF resin given on a 60.0% solids basis – see Tables 5.3 and 5.5 [1].

2) There is a significant amount of water recycling back into the resin [1].

[3] Emissions data reported in survey [1]. BOD and TSS stand for biological oxygen demand and total suspended solids, respectively.
[4] CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant 1].
[5] GHG, VOC, and HAP stand for greenhouse gas, volatile organic compound, and hazardous air pollutant, respectively [1].
[6] Data per 1 kg PRF 100% solids are calculated by Athena. To determine the LCI data for a resin 100% solids, divide the PRF 60% solids data in this table by the decimal value of its stated use solids percentage (0.60) [1]
[7] It takes 1.2 kg of methanol to produce 1.0 kg of formaldehyde [1].
[8] ecoinvent v3.7.1 2021 eco-Query, data are not available for PRF resin. Data are only available for a generic phenol resin (novolac resins, with F/P ratio of 0.5)- see Table A.1.
[9] The amount of water for producing PRF resin was not specified in Table 4.3, Wilson 2009 [1].

Table A.8.2 Benchmarked LCI data - Molar ratio of formaldehyde to phenol plus resorcinol for PRF resin (100% solids)

Inputs	**Molar Mass (g/mol)**	**Wilson 2009 [1]**		
		Mass (in gram)	**No. of moles**	**Molar ratio**
Methanol	32.0			
Formaldehyde	30.0	143.1	4.8	
Phenol	94.1	461.7	4.9	**0.6**[1] [2]
Resorcinol	110.1	316.7	2.9	

Notes to Table A.8.2:
[1] Molar ratio is dimensionless quantity.
[2] *"The molar ratio of formaldehyde to phenol plus resorcinol was used as a check on the quality of the data". [1].*

Annex B Data Quality Assessment

Table B.1. LCI datasets used per wood resin

LCI datasets	Comments
Source: SimaPro LCA Software, v9.2.0.2, 2021, ecoinvent 3.7.1, Allocation, Cut-off by classification, 2021; U.S. LCI Database, 2015.	Geography: U.S. or adjusted to U.S. Technology: Industry average or conventional Timeline: In general, data are not older than 10 years.

Wood Resin	LCI dataset	LCI database	Type of Chemical
UF (amino resin)			
Urea	Urea {RNA}| urea production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Formaldehyde	Formaldehyde {US}| production |Cut-off, U, project	primary data, 2019	Organic
Methanol	Methanol, at plant, {US}	U.S. LCI database	Organic
Formic acid	Formic acid {US/RoW}| market for | Cut-off, U	ecoinvent v3.7.1	Acids, organic
Ammonium sulfate	Ammonium sulfate {US/RoW}| ammonium sulfate production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {US/RoW}| production| Cut-off, U	ecoinvent v3.7.1	Inorganic
Other additives	Chemical, organic {GLO}| production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Water	water, decarbonised {US}| water production, decarbonised | Cut-off, U	ecoinvent v3.7.1	water
MUF (amino resin)			
Melamine	Melamine {US/RoW}| production | Cut-off, U	ecoinvent v3.7.1	Organic
Urea	Urea {RNA}| urea production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Formaldehyde	Formaldehyde {US}| production |Cut-off, U, project	primary data, 2019	Organic
Methanol	Methanol, at plant, {US}	U.S. LCI database	Organic
Formic acid	Formic acid {US/RoW}| market for | Cut-off, U	ecoinvent v3.7.1	Acids, organic
Ammonium sulfate	Ammonium sulphate {US/RoW}| ammonium sulfate production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {US/RoW}| production| Cut-off, U	ecoinvent v3.7.1	Inorganic
Ammonium hydroxide	ammonia, anhydrous, liquid {RNA}| ammonia production, steam reforming, liquid | Cut-off, U	ecoinvent v3.7.1	Inorganic
Other additives	Chemical, organic {GLO}| production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Water	water, decarbonised {US}| water production, decarbonised | Cut-off, U	ecoinvent v3.7.1	water
MF (amino resin)			
Melamine	Melamine {US/RoW}| production | Cut-off, U	ecoinvent v3.7.1	Organic
Formaldehyde	Formaldehyde {US}| production |Cut-off, U, project	primary data, 2019	Organic
Methanol	Methanol, at plant, kg	U.S. LCI database	Organic
Water	water, decarbonised {US}| water production, decarbonised | Cut-off, U	ecoinvent v3.7.1	water
PF (phenolic resin)			
Phenol	Phenol {US/RoW}| production | Cut-off, U	ecoinvent v3.7.1	Organic
Formaldehyde	Formaldehyde {US}| production |Cut-off, U, project	primary data, 2019	Organic
Methanol	Methanol, at plant, {US}	U.S. LCI database	Organic

Wood Resin	LCI dataset	LCI database	Type of Chemical
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {US/RoW}| production| Cut-off, U	ecoinvent v3.7.1	Inorganic
Urea	Urea {RNA}| urea production | Cut-off, U	ecoinvent v3.7.1	Inorganic
Water	water, decarbonised {US}| water production, decarbonised | Cut-off, U	ecoinvent v3.7.1	water
PRF (phenolic resin)			
Phenol	Phenol {US/RoW}| production | Cut-off, U	ecoinvent v3.7.1	Organic
Resorcinol	Benzene {GLO}| market for | Cut-off, U	LCI dataset, default	Organic
	Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	ecoinvent v3.7.1	Inorganic
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	ecoinvent v3.7.1	Inorganic
Formaldehyde	Formaldehyde {US}| production |Cut-off, U, project	primary data, 2019	Organic
Methanol	Methanol, at plant, {US}	U.S. LCI database	Organic
Ethanol	Ethanol, without water, in 99.7% solution state, from ethylene {US/RoW}| ethylene hydration | Cut-off, U	ecoinvent v3.7.1	Organic
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {US/RoW}| production| Cut-off, U	ecoinvent v3.7.1	Inorganic
Water	water, decarbonised {US}| water production, decarbonised | Cut-off, U	ecoinvent v3.7.1	water
EPI and PEP resins			
Base	Water-based polymer emulsion	primary data, 2019	organic
Cross-linker	Polyurethane	primary data, 2019	organic
Inputs/Outputs from/to Technosphere	**LCI dataset**	**LCI database**	
Electricity	Electricity, medium voltage {US}| market group for | Cut-off, U	ecoinvent v3.7.1	
Natural gas	Heat, district or industrial, natural gas {US}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U, m3	ecoinvent v3.7.1	
Propane	Propane, burned in building machine {GLO}| propane, burned in building machine | Cut-off, U	ecoinvent v3.7.1	
Transport	Transport, combination truck, long-haul, diesel powered/tkm/RNA	U.S. LCI database	
	Transport, combination truck, short-haul, diesel powered/tkm/RNA	U.S. LCI database	
	Transport, single unit truck, long-haul, diesel powered/tkm/RNA	U.S. LCI database	
	Transport, single unit truck, short-haul, diesel powered/tkm/RNA	U.S. LCI database	
	Transport, freight train {US}| market for | Cut-off, U	U.S. LCI database	
Waste	Inert waste {US/RoW}| treatment of, sanitary landfill | Cut-off, U	ecoinvent v3.7.1	
	Hazardous waste, for incineration {US/RoW}| treatment of hazardous waste, hazardous waste incineration | Cut-off, U	ecoinvent v3.7.1	
	Municipal solid waste {US/RoW}| treatment of, incineration | Cut-off, U	ecoinvent v3.7.1	

Notes to Table B.1:

[1)] All chemical weights given at 100% non-volatile solids or dry.

[2] New NA LCI data for methanol are available online at Federal Commons website, U.S. LCI database 2021 and were typed in SimaPro 9.2.0.2 2021- see Table B.2.

[3] Resorcinol data is not available in ecoinvent v3.7.1 or U.S. LCI Database. A generic LCI dataset was developed for the purpose of this LCA project- see Table B.3.

[4] "Water, decarbonised {US}| water production, decarbonised | Cut-off, U"- dataset was created specifically for use in water cooling towers. The decarbonization process is meant to remove organic suspended matter, as well as calcium bicarbonate" [10].

[5] "Sodium hydroxide, without water, in 50% solution state {US/RoW}| production| Cut-off, U"- dataset is a mix of 19% diaphragm cell, 80% membrane cell, and 1% mercury cell production technologies [10].

[6] "Formic acid {US/RoW}| market for | Cut-off, U"- dataset is a mix of 2% decarboxylative cyclization of the adipic acid, 85% methyl formate, and 13% oxidation of the butane production routes [10].

[7] Any "unspecified additive" data gap is filled in with two generic LCI datasets, as appropriate (conservative assumptions): *Chemical, organic {GLO}| production | Cut-off, U*; *Chemical, inorganic {GLO}| production* | Cut-off, U.

Table B.2 LCI data for the production of methanol (Franklin Associates 2020)

Inputs/Outputs[1]	**Unit**	**Amount**
INPUTS		
Oxygen	kg	380
Natural gas	kg	620
Energy		
Electricity from grid	kWh	252
Natural gas	m3	7.37
Water consumption		
Water	L	394
Transport[2]		
Pipeline	t*km	499
OUTPUTS		
Methanol	kg	1,000
Emissions to air		
Carbon dioxide, fossil	kg	390
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	0.5
Carbon monoxide	kg	0.72
Nitrogen oxides	kg	1.11
Particulates, < 10um	kg	0.26
Particulates, < 2.5 um	kg	0.26
Sulfur oxides	kg	0.33
Methane	kg	4.59
Nitrogen dioxide	kg	0.01
Solid Wastes		
Non-hazardous waste to landfill	kg	0.26
Solid waste sold for recycling or reuse	kg	0.21
Hazardous waste for disposal	kg	0.0069
Hazardous waste, recovery	kg	0.0085

Notes to Table B.2:

1) SimaPro 9.2.0.2 2021, U.S. LCI database 2015 contains outdated LCI data for methanol production based on Franklin Associates, Cradle-to-Gate Life Cycle Inventory of Nine Plastics Resins and Four Polyethylene Precursors, 2011.

New LCI data for the methanol production are available online at Federal Commons website, U.S. LCI database 2021, *Methanol, at plant, kg, 31-33: Manufacturing 3251: Basic Chemical Manufacturing*. All input and emissions data for methanol production is from GREET 2017. Data generator: Franklin Associates, A Division of ERG; Publication: Franklin Associates (2019) Cradle-to-Resin LCA PET for NAPCOR. https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/6b0d74c7-e880-4b93-aa2f-b777ac183f84, accessed 29-12-2021.

2) In March 2020, Franklin Associates published a revised version of the Cradle-to-Resin LCA PET report from 2019 [14]. Revised transportation data for the methanol production are used for this LCA study. https://napcor.com/sustainability/life-cycle-analysis/, accessed 29-12-2021.

Table B.3 LCI data for the production of resorcinol

Inputs/Outputs	Unit	Amount
INPUTS		
Materials[1)]		
Benzene {GLO}| market for | Cut-off, U	kg	0.232
Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	kg	0.583
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	kg	0.238
Energy[2)]		
Electricity, medium voltage {US}| market group for | Cut-off, U	kWh	0.333
Heat, district, or industrial, natural gas {RoW}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	MJ	2.000
Water[3)]		
Water, decarbonised {US}| water production, decarbonised | Cut-off, U	kg	24.0
OUTPUTS		
Resorcinol, at plant, 2020	kg	1.0
Emissions to air, water, land- n/a		

Notes to Table B.3:

1) Resorcinol, also called m-dihydroxybenzene, phenolic compound used in the manufacture of resins. It is produced in large quantities by sulfonating benzene with fuming sulfuric acid and fusing the resulting benzenedisulfonic acid with caustic soda (sodium hydroxide), https://www.britannica.com/science/resorcinol.

For the production of 1 kg resorcinol, the following stoichiometric inputs were considered as raw materials in this inventory (yield=95%): 0.232 kg benzene (MM=78.1 g/mol); 0.583 kg sulfuric acid (MM=98.1 g/mol); and 0.238 kg caustic soda (MM= 40.0 g/mol).

2) Default energy data for chemical production – based on Table 25.2 [11].

3) Default water data (cooling) for chemical production – based on Table 25.2 [11].

Annex C Sensitivity Check Results

Annex C.1 Sensitivity Analysis Results

Table C.1.1 Sensitivity analysis results for 1,000 kg of formaldehyde (100% solids)

LCIA and energy indicators	Unit	Base case	Scenario case	Deviation- in absolute basis	Deviation- in %
IPCC 2013 AR5 GWP 100a	kg CO_2 eq	1,259.1	1,286.3	-27.2	-2.2%
Ozone depletion potential, ODP	kg CFC-11 eq	3.3E-04	3.3E-04	-5.8E-06	-1.8%
Smog formation potential, SFP	kg O_3 eq	69.7	69.4	0.4	0.5%
Acidification potential, AP	kg SO_2 eq	4.18	4.14	0.04	0.9%
Eutrophication potential, EP	kg N eq	1.6	1.5	0.2	10.6%
Abiotic depletion	kg Sb eq	1.2E-05	1.1E-05	1.3E-06	10.7%
Abiotic depletion potential, ADPf	MJ	35,521.2	35,989.9	-468.7	-1.3%
RPRE, LHV	MJ	374	332	42.4	11.3%
RPRM, LHV	MJ	0	0	0	0%
NRPRE, LHV	MJ	36,784.8	37,107.2	-322.4	-0.9%
NRPRM, LHV	MJ	0	0	0	0%
Secondary materials, SM	kg	0	0	0	0%
Renewable secondary fuels, RSF, LHV	MJ	0	0	0	0%
Non-renewable secondary fuels, NRSF, LHV	MJ	0	0	0	0%
Recovered energy, RE, LHV	MJ	0	0	0	0%
Consumption of freshwater	m^3	1.3	1.3	0	0%
Hazardous waste disposed, HWD	kg	0.018	0.018	0	0%
Non-hazardous waste disposed, NHWD	kg	4.3	4.3	0	0%
High-level radioactive waste, HLRW	m^3	7.7E-07	6.8E-07	8.9E-08	11.5%
Intermediate- and low-level radioactive	m3	1.1E-05	1.0E-05	1.0E-06	9.0%
Components for re-use, CRU	kg	0	0	0	0%
Materials for recycling, MR	kg	0	0	0	0%
Materials for energy recovery, MER	kg	0	0	0	0%
Recovered energy exported, EE, LHV	MJ	0	0	0	0%

Table C.1.2 Sensitivity analysis results for 1,000 kg of UF resin (100% solids)

LCIA and energy indicators	Unit	Base case	Scenario case	Deviation- in absolute basis	Deviation- in %
IPCC 2013 AR5 GWP 100a	kg CO_2 eq	1,530.0	1,526.2	3.7	0.2%
Ozone depletion potential, ODP	kg CFC-11 eq	3.2E-04	3.2E-04	2.9E-07	0.1%
Smog formation potential, SFP	kg O_3 eq	77.0	76.8	0.2	0.2%
Acidification potential, AP	kg SO_2 eq	5.76	5.75	0.01	0.1%
Eutrophication potential, EP	kg N eq	1.6	1.6	0.03	2.2%
Abiotic depletion	kg Sb eq	3.3E-04	3.3E-04	3.4E-07	0.1%
Abiotic depletion potential, ADPf	MJ	35,929.6	35,890.6	39.0	0.1%
RPRE, LHV	MJ	327	318	8.7	2.7%
RPRM, LHV	MJ	0	0	0	0%
NRPRE, LHV	MJ	36,794.7	36,725.8	68.9	0.2%
NRPRM, LHV	MJ	0	0	0	0%
Secondary materials, SM	kg	0	0	0	0%
Renewable secondary fuels, RSF, LHV	MJ	0	0	0	0%
Non-renewable secondary fuels, NRSF, LHV	MJ	0	0	0	0%
Recovered energy, RE, LHV	MJ	0	0	0	0%
Consumption of freshwater	m3	1.4	1.4	0	0%
Hazardous waste disposed, HWD	kg	0.029	0.029	0	0%
Non-hazardous waste disposed, NHWD	kg	3.3	3.3	0	0%
High-level radioactive waste, HLRW	m3	6.0E-07	5.8E-07	1.8E-08	3.0%
Intermediate- and low-level radioactive	m3	1.7E-05	1.7E-05	3.4E-07	2.0%
Components for re-use, CRU	kg	0	0	0	0%
Materials for recycling, MR	kg	0	0	0	0%
Materials for energy recovery, MER	kg	0	0	0	0%
Recovered energy exported, EE, LHV	MJ	0	0	0	0%

Table C.1.3 Sensitivity analysis results for 1,000 kg of MUF resin (100% solids)

LCIA and energy indicators	Unit	Base case	Scenario case	Deviation- in absolute basis	Deviation- in %
IPCC 2013 AR5 GWP 100a	kg CO2 eq	1,518.1	1,522.7	-4.6	-0.3%
Ozone depletion potential, ODP	kg CFC-11 eq	3.2E-04	3.2E-04	2.5E-07	0.1%
Smog formation potential, SFP	kg O3 eq	74.3	74.2	0.1	0.1%
Acidification potential, AP	kg SO2 eq	5.66	5.67	0.0	-0.2%
Eutrophication potential, EP	kg N eq	1.6	1.7	-0.1	-4.2%
Abiotic depletion	kg Sb eq	3.3E-04	3.3E-04	-5.2E-07	-0.2%
Abiotic depletion potential, ADPf	MJ	35,640.9	35,669.4	-28.4	-0.1%
RPRE, LHV	MJ	333	350	-16.6	-5.0%
RPRM, LHV	MJ	0	0	0	0%
NRPRE, LHV	MJ	36,517.7	36,603.5	-85.8	-0.2%
NRPRM, LHV	MJ	0	0	0	0%
Secondary materials, SM	kg	0	0	0	0%
Renewable secondary fuels, RSF, LHV	MJ	0	0	0	0%
Non-renewable secondary fuels, NRSF, LHV	MJ	0	0	0	0%
Recovered energy, RE, LHV	MJ	0	0	0	0%
Consumption of freshwater	m3	1.4	1.4	0	0%
Hazardous waste disposed, HWD	kg	0.007	0.007	0	0%
Non-hazardous waste disposed, NHWD	kg	4.7	4.7	0	0%
High-level radioactive waste, HLRW	m3	6.1E-07	6.4E-07	-3.5E-08	-5.7%
Intermediate- and low-level radioactive	m3	1.9E-05	1.9E-05	-4.1E-07	-2.2%
Components for re-use, CRU	kg	0	0	0	0%
Materials for recycling, MR	kg	0	0	0	0%
Materials for energy recovery, MER	kg	0	0	0	0%
Recovered energy exported, EE, LHV	MJ	0	0	0	0%

Table C.1.4 Sensitivity analysis results for 1,000 kg of MF resin (100% solids)

LCIA and energy indicators	Unit	Base case	Scenario case	Deviation- in absolute basis	Deviation- in %
IPCC 2013 AR5 GWP 100a	kg CO2 eq	5,274.8	5,273.2	1.6	0.03%
Ozone depletion potential, ODP	kg CFC-11 eq	4.3E-04	4.3E-04	-2.0E-07	0.0%
Smog formation potential, SFP	kg O3 eq	261.2	261.1	0.1	0.1%
Acidification potential, AP	kg SO2 eq	24.93	24.91	0.01	0.1%
Eutrophication potential, EP	kg N eq	10.1	10.1	0.04	0.4%
Abiotic depletion	kg Sb eq	9.4E-04	9.4E-04	2.9E-07	0.0%
Abiotic depletion potential, ADPf	MJ	79,385.8	79,377.2	8.7	0.0%
RPRE, LHV	MJ	1,320	1,310	9.4	0.7%
RPRM, LHV	MJ	0	0	0	0%
NRPRE, LHV	MJ	80,865.5	80,824.5	41.0	0.1%
NRPRM, LHV	MJ	0	0	0	0%
Secondary materials, SM	kg	0	0	0	0%
Renewable secondary fuels, RSF, LHV	MJ	0	0	0	0%
Non-renewable secondary fuels, NRSF, LHV	MJ	0	0	0	0%
Recovered energy, RE, LHV	MJ	0	0	0	0%
Consumption of freshwater	m3	1.3	1.3	0	-5%
Hazardous waste disposed, HWD	kg	0.014	0.014	0	0%
Non-hazardous waste disposed, NHWD	kg	2.4	2.4	0	0%
High-level radioactive waste, HLRW	m3	1.1E-06	1.1E-06	2.0E-08	1.8%
Intermediate- and low-level radioactive	m3	5.1E-05	5.0E-05	2.3E-07	0.5%
Components for re-use, CRU	kg	0	0	0	0%
Materials for recycling, MR	kg	0	0	0	0%
Materials for energy recovery, MER	kg	0	0	0	0%
Recovered energy exported, EE, LHV	MJ	0	0	0	0%

Table C.1.5 Sensitivity analysis results for 1,000 kg of PF resin (100% solids)

LCIA and energy indicators	Unit	Base case	Scenario case	Deviation- in absolute basis	Deviation- in %
IPCC 2013 AR5 GWP 100a	kg CO2 eq	2,581.6	2,578.9	2.8	0.1%
Ozone depletion potential, ODP	kg CFC-11 eq	3.2E-04	3.2E-04	4.4E-07	0.1%
Smog formation potential, SFP	kg O3 eq	154.8	155.0	-0.2	-0.1%
Acidification potential, AP	kg SO2 eq	9.15	9.15	0.0	-0.1%
Eutrophication potential, EP	kg N eq	5.8	5.8	0.0	-0.1%
Abiotic depletion	kg Sb eq	1.2E-04	1.2E-04	-5.1E-08	0.0%
Abiotic depletion potential, ADPf	MJ	63,042.1	63,000.7	41.4	0.1%
RPRE, LHV	MJ	1,123	1,125	-1.6	-0.1%
RPRM, LHV	MJ	0	0	0	0%
NRPRE, LHV	MJ	66,434.8	66,399.0	35.7	0.1%
NRPRM, LHV	MJ	0	0	0	0%
Secondary materials, SM	kg	0	0	0	0%
Renewable secondary fuels, RSF, LHV	MJ	0	0	0	0%
Non-renewable secondary fuels, NRSF, LHV	MJ	0	0	0	0%
Recovered energy, RE, LHV	MJ	0	0	0	0%
Consumption of freshwater	m3	1.8	1.8	0	0%
Hazardous waste disposed, HWD	kg	0.039	0.039	0	0%
Non-hazardous waste disposed, NHWD	kg	5.6	5.6	0	0%
High-level radioactive waste, HLRW	m3	1.9E-06	1.9E-06	-3.4E-09	-0.2%
Intermediate- and low-level radioactive	m3	2.5E-05	2.5E-05	-3.9E-08	-0.2%
Components for re-use, CRU	kg	0	0	0	0%
Materials for recycling, MR	kg	0	0	0	0%
Materials for energy recovery, MER	kg	0	0	0	0%
Recovered energy exported, EE, LHV	MJ	0	0	0	0%

Table C.1.6 Sensitivity Analysis Results for 1,000 kg of PRF resin (100% solids)

LCIA and energy indicators	Unit	Base case	Scenario case	Deviation- in absolute basis	Deviation- in %
IPCC 2013 AR5 GWP 100a	kg CO2 eq	2,708.0	2,690.2	17.9	0.7%
Ozone depletion potential, ODP	kg CFC-11 eq	2.5E-04	2.5E-04	2.7E-06	1.1%
Smog formation potential, SFP	kg O3 eq	225.2	225.9	-0.7	-0.3%
Acidification potential, AP	kg SO2 eq	12.92	12.94	0.0	-0.2%
Eutrophication potential, EP	kg N eq	6.6	6.6	0.0	-0.3%
Abiotic depletion	kg Sb eq	5.3E-03	5.3E-03	-1.5E-07	0.0%
Abiotic depletion potential, ADPf	MJ	62,828.9	62,562.0	266.8	0.4%
RPRE, LHV	MJ	1,227	1,232	-4.7	-0.4%
RPRM, LHV	MJ	0	0	0	0%
NRPRE, LHV	MJ	66,283.6	66,033.1	250.6	0.4%
NRPRM, LHV	MJ	0	0	0	0%
Secondary materials, SM	kg	0	0	0	0%
Renewable secondary fuels, RSF, LHV	MJ	0	0	0	0%
Non-renewable secondary fuels, NRSF, LHV	MJ	0	0	0	0%
Recovered energy, RE, LHV	MJ	0	0	0	0%
Consumption of freshwater	m3	1.6	1.6	0	0%
Hazardous waste disposed, HWD	kg	0.070	0.070	0	0%
Non-hazardous waste disposed, NHWD	kg	1.8	1.8	0	0%
High-level radioactive waste, HLRW	m3	1.9E-06	1.9E-06	-9.9E-09	-0.5%
Intermediate- and low-level radioactive	m3	2.6E-05	2.6E-05	-1.1E-07	-0.4%
Components for re-use, CRU	kg	0	0	0	0%
Materials for recycling, MR	kg	0	0	0	0%
Materials for energy recovery, MER	kg	0	0	0	0%
Recovered energy exported, EE, LHV	MJ	0	0	0	0%

Annex C.2 Monte Carlo Uncertainty Analysis Results

As discussed in Section 12, a Monte Carlo uncertainty analysis was also conducted to assess the *combined uncertainty* effect of the data variability (both foreground and background) on the GWP-100 results.

With a confidence level of 95%, the confidence interval of cradle-to-gate GWP-100 of the wood resins are presented in Table C.2. Based on 1,000 runs, such information provides a quantitative indication of the range of GWP-100 results that are likely for all wood resins. In addition, Table C.2 shows the summary results of the uncertainty analysis (mean, median, standard deviation, coefficient of variation, 2.5%, 97.5%, and standard error of median values) for “cradle-to-gate” GWP-100 results of all specified wood resins.

Table C.2 Monte Carlo uncertainty analysis: Cradle-to-gate GWP-100 results of the wood resins and formaldehyde (confidence interval: 95%, 1,000 runs, exported from SimaPro LCA software 9.2.0.2, 2021)

Wood resins and CH2O	Indicator	Unit	Mean	Median	SD1)	CV1)	2.5%	97.5%	SEM1)	Confidence interval in %	
										High	Low
Formaldehyde, 100% solids	GWP-100	kg CO_2 eq	1,293.8	1,267.3	126.8	9.8	1,123.3	1,617.6	4.0	27.6%	-11.4%
UF, 100% solids	GWP-100	kg CO_2 eq	1,566.4	1,556.0	125.8	8.0	1,343.6	1,864.9	4.0	19.8%	-13.7%
MUF, 100% solids	GWP-100	kg CO_2 eq	1,997.6	1,978.4	256.1	12.8	1,554.3	2,556.5	8.1	29.2%	-21.4%
MF, 100% solids	GWP-100	kg CO_2 eq	5,412.0	5,372.1	411.7	7.6	4,699.1	6,412.5	13.0	19.4%	-12.5%
PF, 100% solids	GWP-100	kg CO_2 eq	2,665.3	2,658.6	138.1	5.2	2,416.1	2,955.1	4.4	11.2%	-9.1%
PRF, 100% solids	GWP-100	kg CO_2 eq	2,616.0	2,617.8	117.4	4.5	2,381.3	2,837.3	3.7	8.4%	-9.0%
EPI, 100% solids	GWP-100	kg CO_2 eq	2,007.4	1,997.1	248.1	12.4	1,553.3	2,538.1	7.8	27.1%	-22.2%
PEP, 100% solids	GWP-100	kg CO_2 eq	2,954.7	2,951.1	83.0	2.8	2,796.8	3,123.7	2.6	5.8%	-5.2%

Note to Table C.2:

1) SD, CV, and SEM stand for standard deviation, coefficient of variation, and standard error of mean, respectively.

Annex D Critical Review Statement

Critical Review Statement of Life Cycle Assessment of Wood Product Resin Systems LCA Report

Commissioned by:	U.S. Endowment for Forestry and Communities and, USDA Forest Service Forest Products Laboratory
Conducted by:	Athena Sustainable Materials Institute
External reviewer:	Maureen Puettmann, PhD, WoodLife Environmental Consultants, Corvallis, OR, USA
References:	ISO 14044:2006/Amd.1:2017/Amd.2:2020 – Environmental Management – Life Cycle Assessment – Requirements and Guidelines https://www.iso.org/standard/38498.html?browse=tc ISO 21930:2017 Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services https://www.iso.org/standard/61694.html ISO 14040:2006/Amd.1:2020 – Environmental Management – Life Cycle Assessment – Principles and framework https://www.iso.org/standard/37456.html

Scope of the Critical Review

In accordance with ISO 14044:2006, section 6.1, the goal of the Critical Review was to assess whether:

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

As the study is not intended to support comparative assertions intended to be disclose to the public, the review was performed by an external *reviewer* following ISO 14044:2006, section 6.3.

The reviewer confirm that she has been independent in her role as reviewer in accordance with the ISO 14044 requirements and have no conflicts of interest regarding this review. The review was performed exclusively on the LCA study report and supplementing information available in the public domain.

This review statement is only valid for this specific report titled “A Cradle-to-Gate Life Cycle Assessment of North American Wood Product Resin Systems” and dated February 2022.

Critical Review Process

The critical review was carried out between 06/02/2022 and 04/03/2022 (delivery of the critical review statement).

The review was conducted by exchanging comments and responses using a review template (an Excel spreadsheet) based on Annex A of ISO/TS 14071:2014. There was one formal round of comments and several email conversations in-between.

The overall review was conducted in a professional and constructive manner. All comments were adequately addressed, and all open issues were successfully resolved. There were no conflicting opinions held by any of the involved parties (external reviewer, LCA practitioners, commissioner) upon finalization of the review. A copy of the review report containing all comments and responses is available from the LCA commissioners upon request.

Critical Review Evaluation and Conclusion

The Wood Product Resin Systems LCA Report study is well scoped and adequately supports the goal of understanding the potential environmental impacts of seven wood resins. The study shows a high level of technological knowledge, market relevance, LCA methodological proficiency combined with high quality representative primary data to ensure accuracy of the LCA results.

Based on the final study report and scope of the critical review, it can be **concluded** *that the methods used to carry out the LCA are consistent with the international standard ISO 14044 and ISO 21930, that they are scientifically and technically valid, that the data used are appropriate and reasonable in relation to the goal of the study, and that the interpretations reflect the limitations identified and the goal of the study. The final study report is considered sufficiently transparent and consistent.*

ISO 14044, section 5.2 requires that a third-party report be made publicly available to any third parties other than the practitioner or the commissioner. Confidential contents may be removed from the report prior to sharing it with third parties.

The external reviewer signs this review statement as individual expert. Her signature does not imply an endorsement of the study's scope or results by the affiliated organization.

The external reviewer appreciates the professional responsiveness of Athena LCA team to all queries and comments and that of all parties involved in the review process.

Maureen Puettmann Maureen Puettmann

Valid as of March 4, 2022