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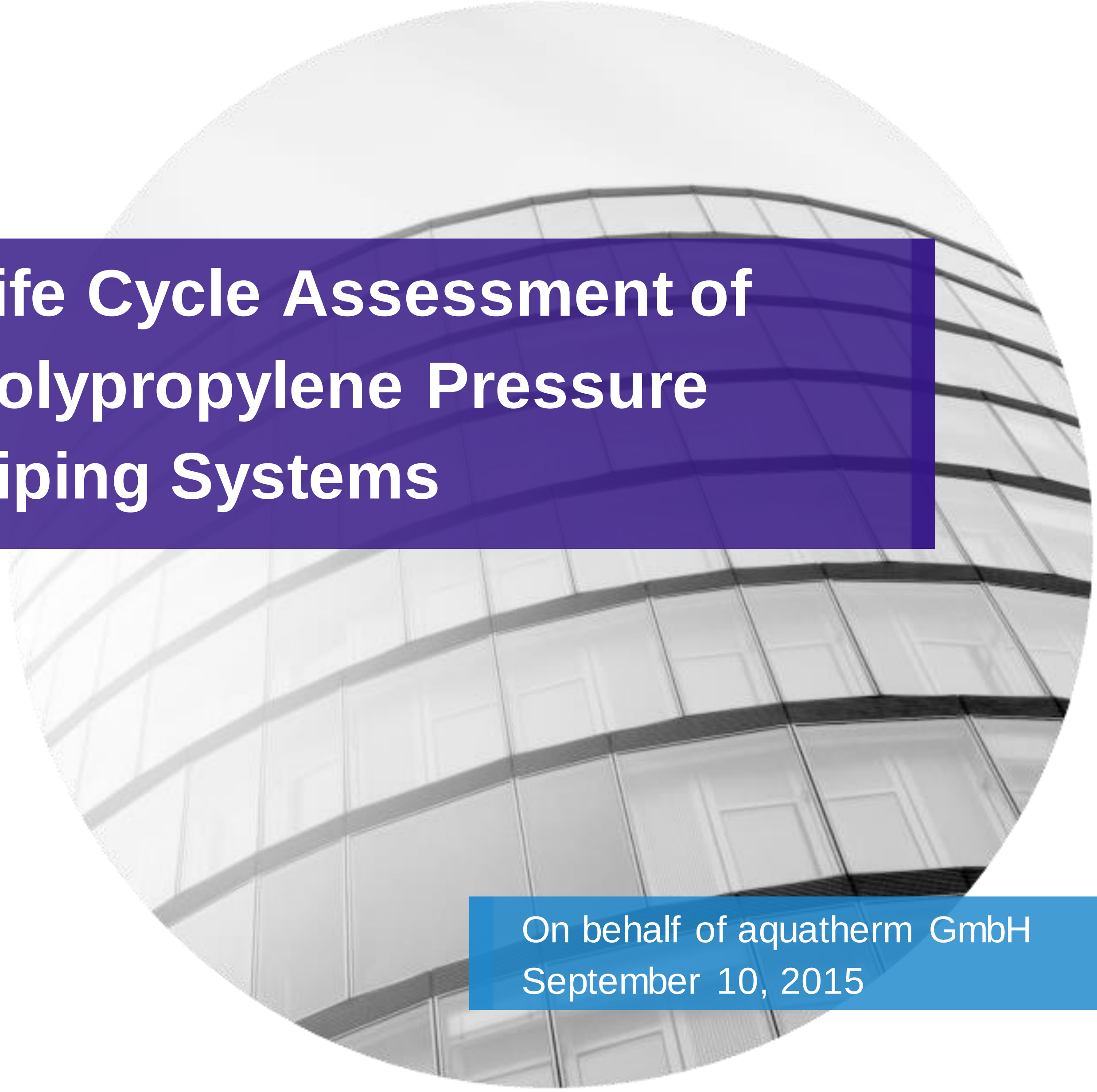

Life Cycle Assessment of Polypropylene Pressure Piping Systems

On behalf of aquatherm GmbH
September 10, 2015

On behalf of thinkstep AG and its subsidiaries

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List of Acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CML	Centre of Environmental Science at Leiden
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
PP-R	Polypropylene Random
SDR	Standard Dimension Ratio
SFP	Smog Formation Potential
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
VOC	Volatile Organic Compound

Glossary

Life cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2)

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" (ISO 14040:2006, section 3.3)

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" (ISO 14040:2006, section 3.4)

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" (ISO 14040:2006, section 3.5)

Functional unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)

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" (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

"An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties."

"A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials."

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it … and/or directly affected by decisions analyzed in the study.” (JRC 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Executive Summary

Aquatherm engaged thinkstep to conduct a life cycle assessment (LCA) study of its polypropylene random copolymer (PP-R) piping systems to produce an Environmental Product Declaration (EPD) for external communication as well as internal understanding of the life cycle impacts of its products. The LCA study was conducted in accordance to ISO 14040/44 and EN 15804 standard, and the verification process was in accordance to the ISO 14025 standard for operating a Product Category Rule (PCR) program. NSF was selected as the program operator, and the external review was performed by PRé Sustainability.

The guiding PCR of the study was published by The Norwegian EPD Foundation in September 2012 (expires September 2017) and entitled *Piping systems for use for sewage and storm water (under gravity).* Additionally, an addendum to the PCR was published by UL Environment in June 2014 (expires June 2016) to include piping systems for general piping systems under gravity and potable water under pressure. The declared unit required a specific length and diameter of piping for a cradle-to-gate study. Thus, 1 meter (3.2 ft) of piping at a diameter of 25 mm (3/4 inch) was selected. The declared product was an representative average of five of the Aquatherm product offering: green, blue, red, lilac, red, and black.

It was found that the mass composition correlated with the cradle-to-gate impact contribution for Global Warming Potential (GWP). Therefore, the polypropylene was the most substantial contributor, followed by the brass fittings. Additives and auxiliary materials such as glass fibers and oxygen barriers has impact contributions that varied among the piping systems. A representative average calculation led to a minor contribution from auxiliary materials. Energy use, chiefly electricity, was also found to have significant impacts. Inbound transportation, packaging, and facility waste treatment were minor contributors.

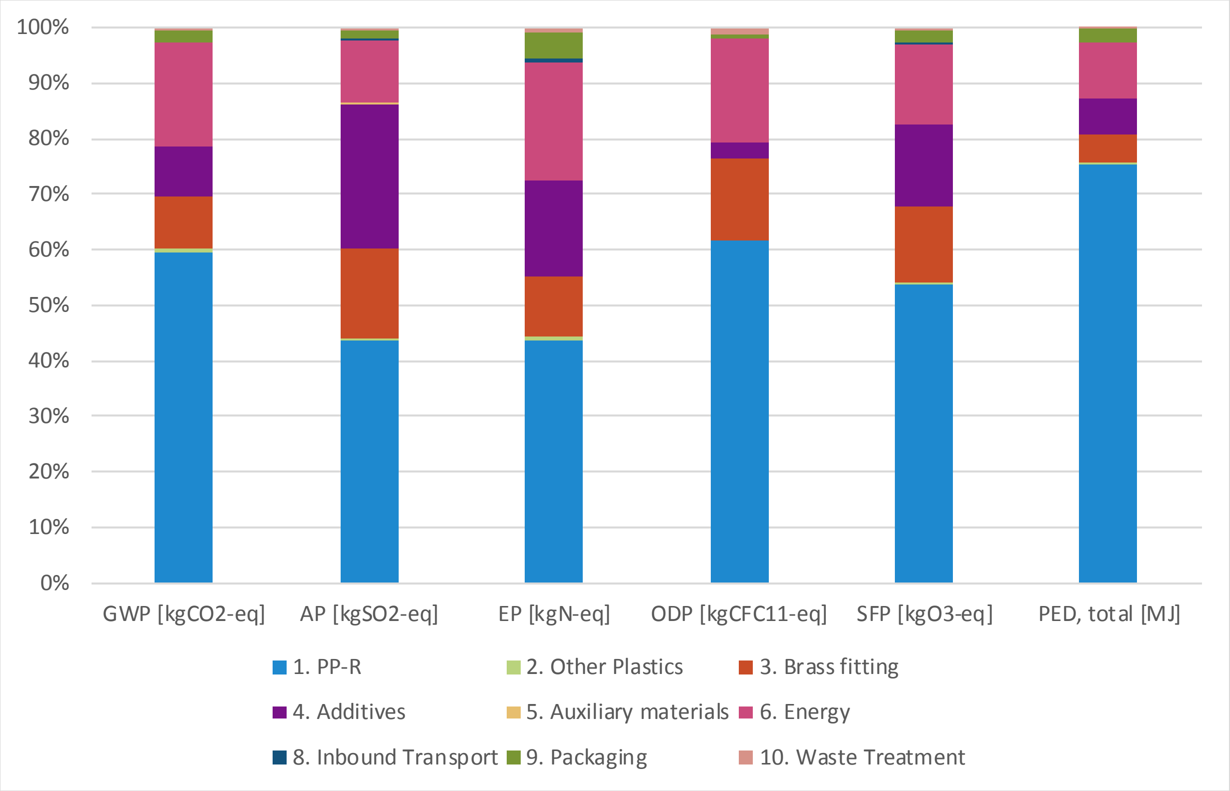

Figure 1-1: TRACI 2.1 impacts and Primary Energy Demand indicator shown for cradle-to-gate system boundary of the representative Aquatherm piping system

The findings from this study suggests that minimizing PP-R and brass material loss and continued energy efficiency improvements would lend to opportunities for impact reduction. Furthermore, exploring the introduction of recycled polymers may lead to further reductions in impacts

1. Goal of the Study

Aquatherm manufactures polypropylene (PP-R) pressure piping systems in Attendorn, Germany for distribution to global markets and is interested in demonstrating leadership in this industry through transparent communication of its products' environmental performance through an Environmental Product Declaration (EPD) in accordance with ISO 14025 and EN 15804. This will enable purchasers of Aquatherm's PP-R pressure piping systems to be eligible for LEED points under the LEED v4 standard. Furthermore, the study will allow Aquatherm to identify key drivers of impacts as well as greatest opportunities for improvement throughout the supply chain. Note that confidential information can be removed prior to sharing the report in accordance with ISO 14044, Section 5.2.

Aquatherm has engaged thinkstep, Inc. to conduct an ISO-conformant LCA study in concurrence with the Product Category Rule (PCR) entitled *Piping systems for use for sewage and storm water (under gravity)* published by The Norwegian EPD foundation in September 2012 with an addendum by UL Environment in June 2014 for *Piping for use under gravity and for potable water (under pressure)*. The EPD program verification process, including a third-party Critical Review, was facilitated by the program operator, NSF International (NSF) to ensure compliance both with the PCR and ISO 14040/44 standards. The results of the study are intended for public distribution as part of a greater effort to clarify the environmental advantage of Aquatherm PP-R pressure piping systems in the market. The intended audience for this report includes the program operator, NSF and reviewers who will be assessing the EPD for conformance to the PCR, as well as Aquatherm internal stakeholders involved in marketing and communications, in operations, and in design. The intended audience for the resulting EPD is the building and construction community including owners, designers, engineers, facility management, specifiers and contractors.

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product System(s)

The study evaluates the environmental impacts of a non-weighted average PP-R piping system (i.e. results are not weighted by production volumes or sales volume). There are five different piping systems averaged in this analysis, as follows:

1. aquatherm green pipe, mechanical piping that is especially suited for potable water and food-grade applications;
2. aquatherm blue pipe, mechanical piping that is especially suited for heated and chilled water, condenser water, and industrial and chemical process systems;
3. aquatherm lilac pipe, mechanical piping that is specifically intended for non-potable, reclaimed or recycled water, rainwater catchment, and irrigation systems; and,
4. aquatherm black system, a radiant panel system that is used to provide energy-efficient radiant heating and cooling for any size building, from single-family homes to large high-rise commercial facilities;
5. aquatherm red pipe, mechanical piping that is specifically intended for light hazard occupancy fire suppression systems.

The analysis discussed in the report will be the representative, average piping system aggregated from the above five systems.

2.2. Declared Unit

With a cradle-to-gate system boundary, a *declared unit* is considered. According to the PCR, the required declared unit is *one piece of pipe with a defined diameter and length*. The declared unit being evaluated, in accordance to the guiding PCR is:

"1 meter of piping system with a 25 mm (¾ inch) outer diameter"

The reference flow of the declared unit is 0.2346 kg of piping system comprised of pipe and fittings. The 25mm outer diameter (OD) pipe is assigned to a ¾ inch equivalent copper pipe, because of the similarity between the pipes' flow cross sections. A 25mm OD pipe has an internal diameter of 18 mm, which is the nearest to a ¾ inch copper pipe. A ¾ inch nominal/equivalent diameter is offered in all five piping systems; therefore, it was selected as the defined size. The available *standard dimension ratio (SDR)*—the ratio between the pipe diameter and the pipe wall thickness—varies within and between systems.

2.3. System Boundaries

The PCR requires, at minimum, that the EPD report environmental impacts of activities up to the factory "gate", with subsequent life cycle stages optionally reported. This is considered by the PCR to be the cradle-to-gate system boundary. According to the EN 15804 standard on the sustainability of construction works, cradle-to-gate activities, or product stage activities, can be grouped into three modules: raw material production, inbound transport, and manufacturing, which are categorized as *A1, A2,* and *A3*, respectively (Figure 2-1). Raw material production includes extraction of new materials, reuse of materials from previous systems, and processing of secondary materials. Transport includes fuel production and vehicle tailpipe emissions for inbound raw materials. Manufacturing includes production of ancillary products (metal components, fasteners, supports, etc.), and manufacturing of products (pipes, fittings and valves), co-products, and packaging.

Product Stage			Construction Stage		Use Stage					End-of-Life Stage				Next Product System
A1	**A2**	**A3**	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw materials supply	**Transport**	**Manufacturing**	Transport	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction	Transport	Waste processing	Disposal	Reuse, recovery or recycling potential

Figure 2-1: Life cycle stages of construction products according to EN 15804 standard

The EN 15804 stages included in the system boundary are A1-A3. Transport to the construction site and impacts from installation, use, and end-of-life are excluded due to lack of available data and wide variation in these phases globally. Thus, life cycle modules A4 and after are excluded from the study. Table 2-1 summarizes the included and excluded activities in this study.

Table 2-1: System boundaries

Included	Excluded
✓ A1: Raw material supply	× A4: Transport to building site
✓ A2: Transport to manufacturer	× A5: Construction activities
✓ A3: Manufacturing	× A5: Disposal of packing material
	× Use stage (B1-B5)
	× B6: Building operational energy use
	× B7: Building operational water use
	× C1: Demolition
	× C2: Waste transport
	× C3: Waste processing
	× C4: Disposal
	× D: Recycling potential

Included	Excluded
	✗ Construction and maintenance of capital equipment ✗ Maintenance and operation of support equipment ✗ Human labor and employee commute

2.3.1. Time Coverage

Annual data from 2014 were collected for pipe system manufacturing facilities. Background data (mainly raw materials, chemicals, fuels, and electricity) were obtained from the GaBi database with reference years between 2010 and 2014.

2.3.2. Technology Coverage

The data represent the technology used at the pipe and fitting manufacturing plant. In this study, site-specific data representative of the technology used in Germany in the reference year 2014 were collected and analyzed. In cases when no primary data were available, either estimations provided by the involved companies or calculated data were used.

2.3.3. Geographical Coverage

The geographical coverage for the production of PP-R pressure piping systems is Germany. Whenever Germany background data were not available, European, North American, or global data were used as proxies.

2.3.4. Multi-output Allocation

Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step is applied and documented along with the process in Chapter 3.

Aquatherm's facilities manufacture multiple PP-R pressure piping products. Aquatherm data was used in estimating the electricity consumption per mass of product. Facility inputs and outputs, where product-level information was not available, were allocated based on the total mass of product throughput at each facility. Natural gas, propane, and water input data were collected at the facility level, and allocated to individual product by annual production masses. Material inputs and outputs which were not available at the product level—scrap, secondary and tertiary packaging, and wastes—were allocated similarly.

Allocation of background data (energy and materials) taken from the GaBi 2014 databases is documented online at http://www.gabi-software.com/america/support/gabi/

2.3.5. Manufacturing Waste Allocation

End-of-Life allocation generally follows the requirements of ISO 14044, section 4.3.4.3.

Metals and polymer recycling (avoided burden approach): Benefits from internal material recycling were credited to the system through displacement of virgin material production, minus burdens from the recycling process.

Landfilling (avoided burden approach): In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilization rates (flaring vs. power production).

Paper and cardboard recycling (cut-off approach): Any scrap inputs into manufacturing were assumed to enter the system burden-free. The system boundary at end of life is drawn after scrap collection to account for the collection rate, which generates an open scrap output for the product system. The processing and recycling of the scrap is associated with the subsequent product system and is not considered in this study.

2.4. Cut-off Criteria

No cut-off criteria are defined for this study. All available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Chapter 3. The influence of these proxy data on the results of the assessment has been carefully analyzed and is discussed in Chapter 5.

2.5. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-2 and Table 2-3. TRACI 2.1 has been selected as it is currently the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors (Bare 2012, EPA 2012) and the PCR specifies its use for EPDs intended for the North American market. CML 2001 has also been included for EPDs intended for the European market.

Global Warming Potential and Non-Renewable Primary Energy Demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be one of the most pressing environmental issues of our time.

Eutrophication, Acidification, and Photochemical Ozone Creation Potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

Ozone depletion potential was chosen because of its high global relevance, which eventually led to the worldwide ban of more active ozone-depleting substances; the phase-out of less active substances is due to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear fuel production. In addition, the uncontrolled burning of biomass (e.g., slash-and-burn) is known to result in emissions of ozone-depleting substances. The indicator is therefore included for reasons of completeness.

Water consumption, i.e., the anthropogenic removal of water from its watershed through shipment, evaporation, or evapotranspiration, has also been selected due to its high political relevance. The UN estimates that roughly a billion people on the planet don’t have access to improved drinking water, which entails a variety of problems around ecosystem quality, health, and nutrition.

Table 2-2: TRACI 2.1 and CML 2001 impact category descriptions

Impact Category	Description	TRACI 2.1 Unit	CML 2001 Unit	Reference
Global Warming Potential (GWP)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	kg CO_2 equivalent	(Bare, 2012), (EPA, 2012) (Guinée, et al., 2002)
Eutrophication Potential (EP)	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	kg Phosphate equivalent	
Acidification Potential (AP)	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	kg SO_2 equivalent	
Photochemical Ozone Creation Potential (POCP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg O_3 equivalent	kg Ethene equivalent	
Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 equivalent	kg CFC-11 equivalent	

Table 2-3: Other environmental indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	(Guinée, et al., 2002)
Water Consumption	A measure of the net intake and release of fresh water across the life of the product system. This is not an indicator of environmental impact without the addition of information about regional water availability.	Liters of water	(thinkstep, 2014)
Hazardous waste disposal	Waste stream generated by the manufacturer that is required to be treated per regulations in the European Council directives 91/689/EEC and 75/442/EEC	kg disposed	(EU 1991), (EU 1975)

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.6. Interpretation to Be Used

No grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

2.7. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modeling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report.

- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope.

An evaluation of the data quality with regard to these requirements is provided in Section 5.4 of this report.

2.8. Software and Database

The LCA model was created using the GaBi 6 Software system for life cycle engineering, developed by thinkstep AG. The GaBi 2015 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.9. Critical Review

As part of the PCR process, a third-party verifier was selected by NSF International, the PCR Program Operator, to validate the LCA study and subsequent background report and EPD documents. J. Renee Morin at PRé Sustainability was selected by NSF to verify the LCA conducted by thinkstep.

The Critical Review Statement can be found in Annex A.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

All primary data were collected using customized data collection templates, which were sent out by email to Aquatherm. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies were identified, thinkstep engaged with the data provider to resolve any open issues.

3.2. Aquatherm Piping System Description

3.2.1. Overview of Product System

The Aquatherm products include five different piping systems:

- aquatherm green System – potable water service and distribution (plumbing), food-grade, and residential sprinkler, applications.
- aquatherm blue System – pressure piping systems in a wide range of non-potable applications
- aquatherm lilac System – water conservation systems that use water from reclaimed, recycled and rain sources
- aquatherm black System – delivery of radiant heating and cooling using water
- aquatherm red System – specialized for fire sprinkler systems with integrated flame resistance

Procured materials are combined and extruded to desired width and length, while the pipe fittings are injection molded to the corresponding size. Electricity, fuel, and water are required to transform the materials into the desired piping system schematic.

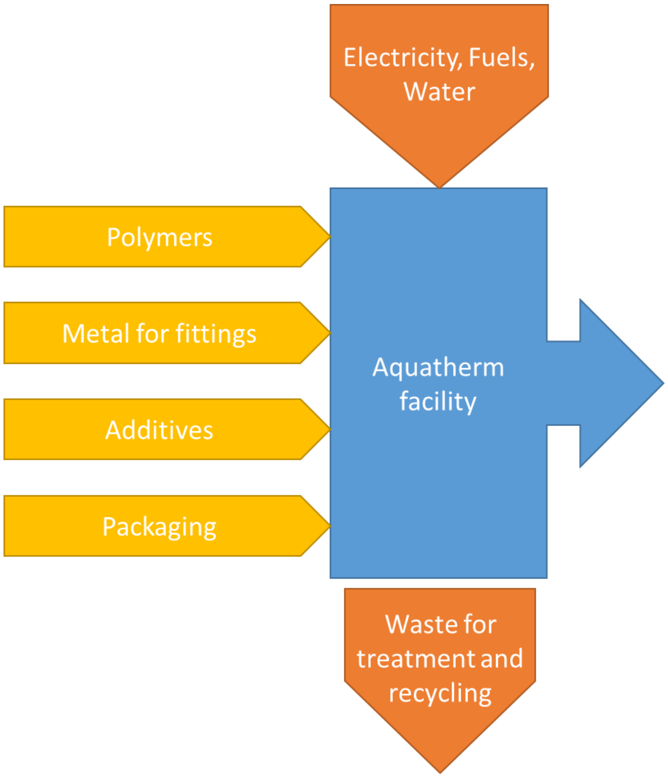

Figure 3-1: General flow diagram of Aquatherm production process

As described in Section 2.1, the representative product for which impacts are reported is a non-weighted average (i.e. piping system impacts are not weighted by production or sales volume) of five piping systems. The amount and type of material of 1 m of piping system differs slightly among products. For example, the *standard dimension ratio* (SDR) offering differs among piping systems, as summarized in Table 3-1.

Table 3-1: Summary of baseline SDR, SDRs offered by piping systems, and calculated pipe wall thickness in mm

Material	Baseline SDR of ¾-in (25mm) pipe	Pipe wall thickness at ¾ (25mm) pipe diameter	SDR Offering for all pipe diameter
Black System	7.5*	3.33	7.5
Blue Pipe	7.4	3.5	7.4, 9, 11, 17.6
Green Pipe	7.4	3.5	7.4, 9, 11
Lilac Pipe	7.4	3.5	7.4, 11
Red Pipe	7.4	3.5	7.4
Average System		**3.47**	

* Pipes in the Black System is square; therefore, the perimeter of the square pipe was used to assume a hypothetical round pipe equivalent

The formula for calculating SDR is as follows: SDR = (pipe outside diameter) / (pipe wall thickness)

Note that higher values of SDR indicates thinner pipe walls. The average, representative piping system under analysis will have a pipe wall thickness of 3.47 mm.

3.2.2. Product Composition

Aquatherm piping system is primarily comprised of polypropylene random copolymer (PP-R). However, other polymers, accessory metals, additives, and reinforcement are also included in the product depending on the piping system. Table 3-2 shows the material composition by mass percentage of the five individual and representative Aquatherm piping system products.

Table 3-2: Material composition of representative and individual piping systems

Material	Average system	Black System	Blue System	Green System	Lilac System	Red System
PP-R Granulate	86.4%	78.8%	83.9%	89.3%	93.2%	86.7%
Other polymers	0.38%	0.38%	0.38%	0.38%	0.38%	0.38%
Brass Fitting	4.75%	4.75%	4.75%	4.75%	4.75%	4.75%
Other Metals	0.28%	0.28%	0.28%	0.28%	0.28%	0.28%
Reinforcement	3.44%	0.00%	6.68%	3.47%	0.00%	7.04%
Additives	1.14%	0.52%	1.03%	1.82%	1.42%	0.91%
Oxygen barrier	3.65%	15.29%	2.94%	0.00%	0.00%	0.00%

The black and some of the blue piping systems uniquely utilize an oxygen barrier layer, and this comprises a significant mass portion for the black system; however, in the average, representative product, the oxygen barrier is a minor component. Overall, the PP-R granulate is the dominant component with 86.37%. Metals for threaded pipe fittings, fiberglass reinforcement, and additives comprise nominal portions of the product.

3.2.3. Manufacturing

At the Aquatherm facility, raw materials are compounded and extruded for the pipe and injection molded for the pipe fittings. Table 3-3 shows the materials and utility inputs required to meet the declared unit of 1m of 25mm (¾ in) piping system.

Table 3-3: Unit process of representative piping system, 1 m length with ¾ in pipe diameter

Type	Flow	Value	Unit	Distance [km]	Mode
Inputs	Electricity	0.175	kWh	n/a	n/a
	Propane	2.48E-04	kg	n/a	n/a
	Water, from river	0.00794	m^3	n/a	n/a
	Additive	0.00395	kg	100	27 ton payload, Euro 0 -5 emissions profile
	Reinforcement	0.00976	kg	9400	27 ton payload, Euro 0 -5 emissions profile
	Metals	0.0136	kg	10	27 ton payload, Euro 0 -5 emissions profile

Type	Flow	Value	Unit	Distance [km]	Mode
	Oil and grease	7.91E-05	kg	100	27 ton payload, Euro 0 -5 emissions profile
	Other polymers	8.79E-04	kg	100	27 ton payload, Euro 0 -5 emissions profile
	Oxygen barrier	0.00142	kg	100	27 ton payload, Euro 0 -5 emissions profile
	Packaging	0.0126	kg	12.5	27 ton payload, Euro 0 -5 emissions profile
	PP-R Granulate	0.207	kg	1250	27 ton payload, Euro 0 -5 emissions profile
	Solvents	2.80E-05	kg	100	27 ton payload, Euro 0 -5 emissions profile
Outputs	Piping system	0.235	kg		
	Plastic scrap for recycling	0.00275	kg		
	Metal scrap for recycling	0.000745	kg		
	Paper for recycling	0.00056	kg		
	Waste for incineration	6.42E-05	kg		
	Waste for disposal	0.00184	kg		
	Water, returned to river	0.00794	m^3		

3.3. Background Data

3.3.1. Fuels, Energy, and Water

German averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2015 databases. Table 3-4 shows the most relevant LCI datasets used in modeling the product systems. Electricity consumption was modeled using a German grid mix that accounts for imports from neighboring countries.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

Table 3-4: Key energy and water datasets used in inventory analysis

Aquatherm Process	Dataset	Data Provider	Reference Year	Location
Electricity	Electricity grid mix	thinkstep AG	2011	Germany
Forklift fuel	Propane at refinery	thinkstep AG	2011	Germany

3.3.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2015 database. The most relevant LCI datasets used in modeling the product systems are summarized in Table 5-1 in Annex A. Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

3.3.3. Transportation

Estimated transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to production and assembly facilities.

The GaBi 2015 database was used to model transportation. Truck transportation was modelled using the GaBi global truck transportation datasets with a mix of the Euro emissions profiles 0 – 5. Average payload of 27 ton was selected. Only one-way inbound transports were considered, as it was assumed that the vehicles enter another life cycle once the Aquatherm-specific materials are delivered to the facility.

3.3.4. Facility Waste Treatment and Recycling

Wastes and potentially recyclable output flows were considered and treated appropriately by applying the relevant GaBi dataset. Non-hazardous flows were considered to be landfilled; hazardous flows were considered to be incinerated in appropriate facilities; plastic scrap were assumed to be sold to external recyclers; cardboard and paperboard, due to the high recycled content of the raw material input, has been cut off from the system per the GaBi modeling principles, available at http://www.gabi-software.com/support/gabi/gabi-modelling-principles/. Plastic scrap recycling has been considered by system expansion to model the displacement of primary plastic production.

There were several wastes streams at the Attendorn, Germany facility where it was necessary to follow the European Union directive 91/689/EEC, Annex III:

- residue from substances employed as solvents—inks and solvents from pipe marking in the extrusion
- mineral oils and oily substances (e.g. cutting sludges, etc.)—hydraulic and gear oil from injection molding machines and extruders and tooling factory

Hazardous wastes are modeled to be incinerated as per Table 3-5.

Table 3-5: Key waste treatment and recycling datasets used in inventory analysis

Aquatherm Process	Dataset	Data Provider	Reference Year	Location
Hazardous waste treatment	Hazardous waste (non-specific) (c rich, worst scenario)*	thinkstep AG	2012	Global
Landfill	Municipal waste landfill (EN15804 C4)	thinkstep AG	2013	Germany
Oil and lubricant incineration	Used oil	thinkstep AG	2013	Germany
Credit for PP recycling	Polypropylene granulate (PP) mix	thinkstep AG	2013	Germany
Credit for plastic film recycling	Polyethylene Film (PE-LD) without additives	thinkstep AG	2013	Germany
Cardboard waste	<Cut-off>	N/A	N/A	N/A

*c rich indicates the worst case scenario of organic hazardous wastes

3.4. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, Table 3-6 only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results.

Table 3-6: LCI results of Aquatherm piping system (in kg per declared unit of 1 m of piping system)

Type	Flow	Unit	Total	Raw Material	Transport	Manufacturing
Resources	Water use*	kg	3.17	3.09	0.0007	0.0751
	Crude oil	kg	0.218	0.214	0.00354	3.61E-04
	Hard coal	kg	0.117	0.0527	0.0638	7.28E-06
	Natural gas	kg	0.158	0.149	0.00883	3.18E-05
	Uranium	kg	2.43E-06	1.32E-06	1.11E-06	1.25E-10
Emissions to air	CO_2 (fossil)	kg	0.579	0.441	0.137	0.00121
	CH_4	kg	2.10E-03	1.87E-03	2.21E-04	1.37E-06
	N_2O	kg	1.65E-05	1.13E-05	5.15E-06	5.77E-08
	NO_x	kg	8.13E-04	6.34E-04	1.79E-04	3.17E-07
	SO_2	kg	1.02E-03	8.82E-04	1.41E-04	4.10E-07
	NMVOC	kg	4.61E-04	4.42E-04	1.85E-05	4.93E-07
	CO	kg	3.52E-04	2.65E-04	8.45E-05	2.08E-06
	PM10	kg	2.75E-07	2.73E-07	1.46E-09	1.05E-11
	PM2.5	kg	2.06E-04	1.98E-04	7.89E-06	1.07E-07
	Heavy metals	kg	3.37E-02	3.37E-02	1.25E-05	1.31E-08
Emissions to water	NO_3^-	kg	5.80E-05	2.87E-05	2.79E-05	9.73E-07
	PO_4^{3-}	kg	1.77E-06	1.24E-06	4.99E-07	3.19E-08
	Heavy metals	kg	1.90E-04	9.71E-05	9.25E-05	1.62E-08
Emissions to soil	PAH	kg	1.41E-10	1.28E-10	1.31E-11	1.18E-15
	Heavy metals	kg	5.44E-04	6.52E-04	-1.09E-04	3.35E-07
Waste treatment	Hazardous waste	kg	6.42E-05	0	0	6.42E-05
	Non-Hazardous waste	kg	0.00184	0	0	0.00184
	Radioactive waste	kg	0	0	0	0

* Water use is presented as net freshwater use

4. Results

This chapter contains the results for the inventory metrics and impact categories defined in section 2.5. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1. Overall EPD Results

The overall cradle-to-gate results are presented broadly into three categories: Raw Material, Transport, and Manufacturing (Figure 4-1). For overall results using the EN 15804 life cycle modules as required by the guiding PCR, refer to the declared results in the EPD. The impacts shown and discussed in this report are for analytical purposes only.

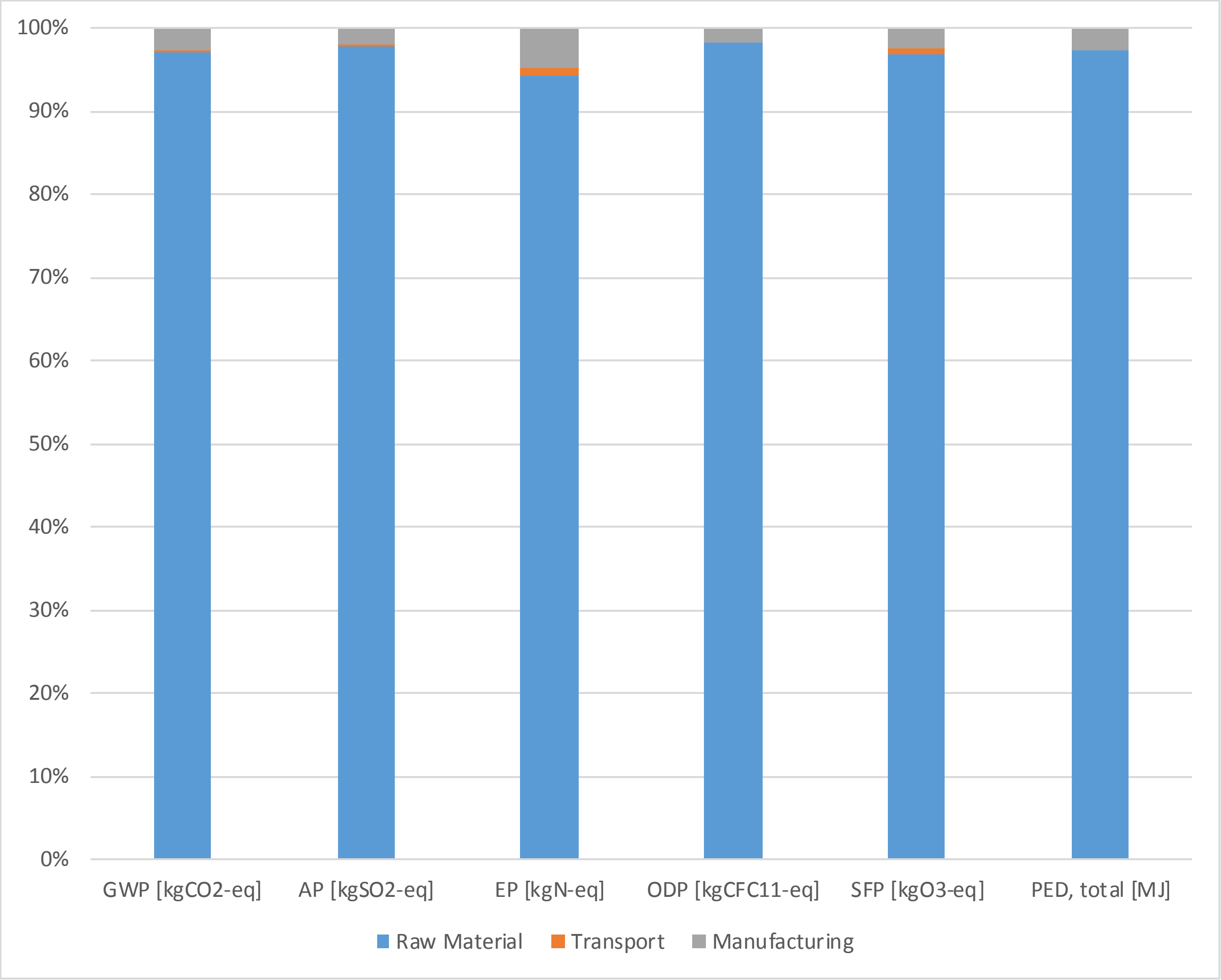

Figure 4-1: TRACI 2.1 impacts and Primary Energy Demand indicator broadly shown for cradle-to-gate system boundary of the representative Aquatherm piping system

Figure 4-2 shows the overall cradle-to-gate TRACI 2.1 impacts and Primary Energy Demand (PED) indicator further subdivided into supply chain categories.

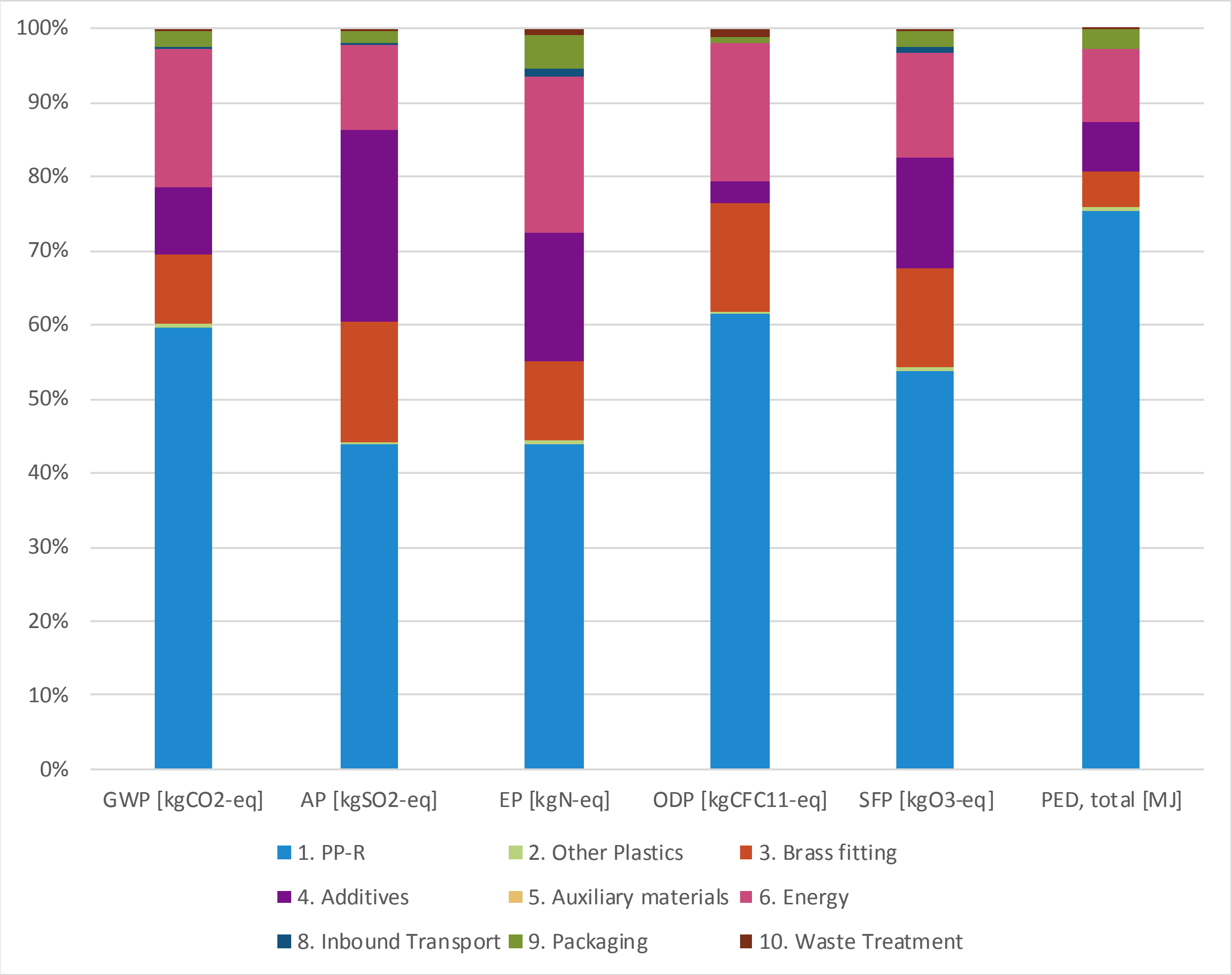

Figure 4-2: TRACI 2.1 impacts and Primary Energy Demand indicator shown for cradle-to-gate system boundary of the representative Aquatherm piping system

Generally, the polymers comprise nearly 50% or more of the impact contribution depending on the impact category. PED is shown to be primarily comprised of polymer granulate; however, this is due to the embodied energy content of the petroleum-based resins rather than fuel consumption upstream. The GaBi dataset for polypropylene has 55% embodied energy; therefore, 45% of the PED from polypropylene is from consumed energy. Energy inputs, the majority of which is electricity, comprises a significant portion of all impact categories. Impacts from metals come primarily from brass, which comprises the majority of metal parts. Depending on the impact category, water and additives inputs have significant contributions, which will be further explored in Section 5. Inbound transport, lubricants and solvents, and waste treatment do not have any appreciable contribution to the life cycle. The absolute impacts equivalent values are summarized below in Table 4-1.

Table 4-1: CML 2001, TRACI 2.1, PED, and Waste outputs absolute equivalency values shown for life cycle categories

	PP-R	Other Plastics	Brass fitting	Additives	Auxiliary Materials	Energy	Inbound Transport	Packaging	Waste Treatment
CML 2001 (April 2013)									
GWP [kg CO_2-eq]	0.348	0.00362	0.0542	0.0534	1.14E-04	0.1086	0.001166	0.0121	0.00278
AP [kg SO_2-eq]	6.88E-04	5.36E-06	2.74E-04	4.58E-04	2.90E-07	1.76E-04	5.04E-06	2.26E-05	6.02E-06
EP [kg PO_4^{3-}eq]	6.78E-05	9.38E-07	2.08E-05	2.32E-05	2.16E-08	2.30E-05	1.38E-06	4.06E-06	2.22E-06
ODP [kg CFC11-eq]	3.5E-11	6.58E-14	8.36E-12	1.64E-12	1.59E-15	1.07E-11	1.406E-15	4.38E-13	6.04E-13
POCP [kg C_2H_4-eq]	1.49E-04	1.25E-06	1.93E-05	1.79E-05	4.44E-08	1.33E-05	-1.91E-06	3.18E-06	7.38E-07
TRACI 2.1									
GWP [kg CO_2-eq]	0.348	0.00362	0.0542	0.0534	1.14E-04	0.1086	0.001166	0.0121	0.00278
AP [kg SO_2-eq]	7.10E-04	6.12E-06	2.62E-04	4.24E-04	2.82E-07	1.83E-04	6.74E-06	2.46E-05	6.72E-06
EP [kg N-eq]	4.12E-05	4.90E-07	1.02E-05	1.64E-05	1.30E-08	1.98E-05	8.18E-07	4.22E-06	9.52E-07
ODP [kg CFC11-eq]	3.72E-11	7E-14	8.9E-12	1.74E-12	1.69E-15	1.14E-11	1.494E-15	4.64E-13	6.42E-13
SFP [kg O_3-eq]	1.09E-02	1.16E-04	2.76E-03	3.02E-03	3.36E-06	2.88E-03	1.40E-04	4.36E-04	6.76E-05
PED, total [MJ]	14.1	0.0876	0.912	1.226	0.00488	1.874	0.01678	0.47	0.024
Hazardous waste [kg]	0	0	0	0	0	0	0	0	6.42E-05
Non-Haz. waste [kg]	0	0	0	0	0	0	0	0	0.00184
Radioactive waste [kg]	0	0	0	0	0	0	0	0	0

4.2. Detailed Raw Material Results

Raw materials category (Polymers, Metals, and Additives from **Figure 4-3**) is comprised of numerous, individual material inputs. Therefore **Figure 4-4** shows the TRACI 2.1 impacts and PED indicator in terms of the individual GaBi datasets contributing to the Raw Material category. The top 10 contributing materials (sorted by GWP) are shown in the figure and the rest grouped into “Other Materials”.

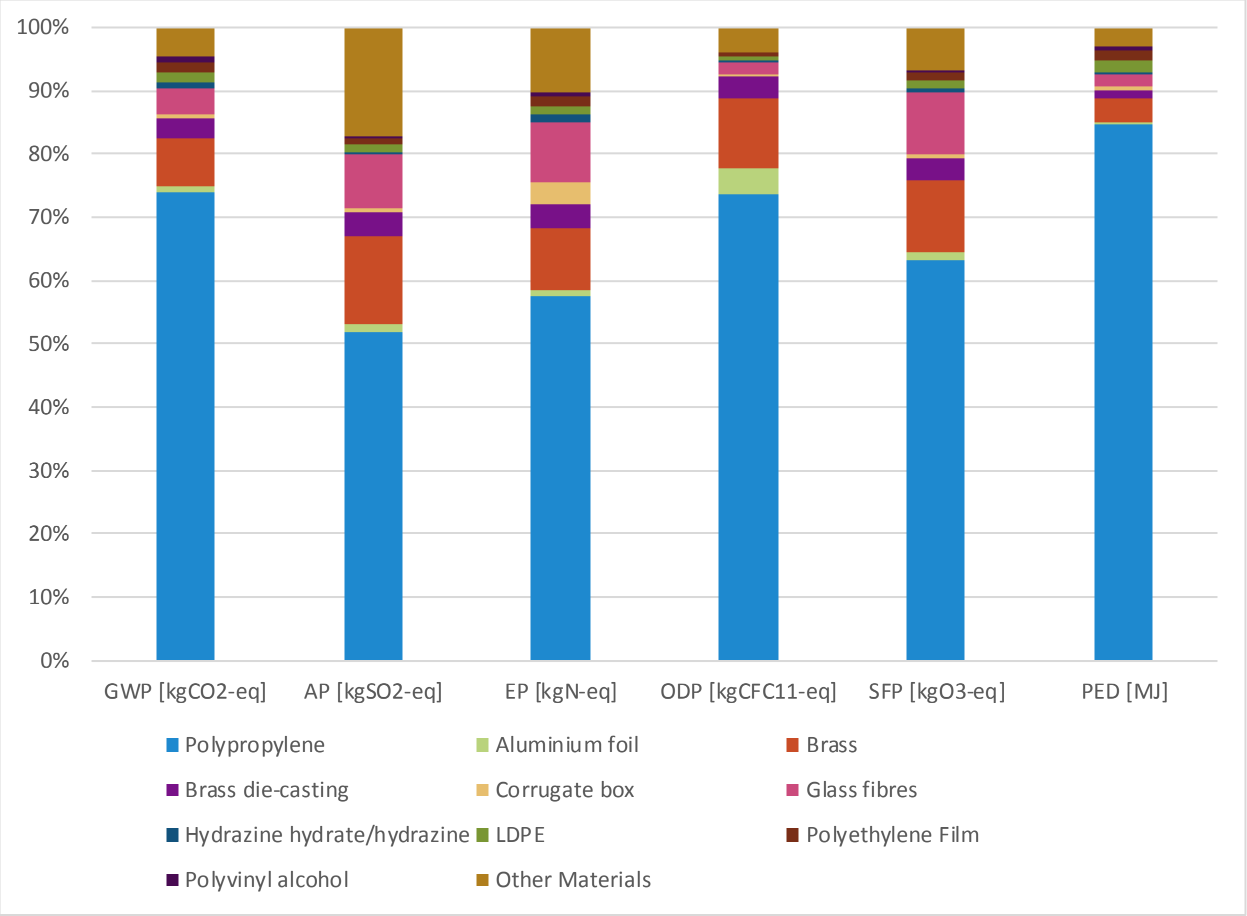

Figure 4-3: TRACI 2.1 impacts and PED indicator for the top 10 (sorted by GWP) individual raw material inputs

The polypropylene resin is the dominant contributor in all categories; however, there are also significant impacts from the brass fitting and glass fiber reinforcement. Due to the fuel combustion-intensive nature of glass production, glass fiber has emissions relevant to Acidification, Eutrophication, and Smog Formation Potentials. Brass production shares these characteristics, but also contributes significantly to Ozone Depletion as well in relation to the overall material inputs for Aquatherm products. Besides polypropylene, brass, and glass fibers, a multitude of minor contributors comprise the remaining impacts from the Raw Material category.

4.3. Sensitivity Analysis

As noted in Table 3-1, the representative product under analysis has an SDR of 7.4 or a pipe wall thickness of 3.47 mm. However, narrower pipe walls are offered. Therefore, a sensitivity analysis is performed to gauge the influence of the pipe wall thickness assumption on the cradle-to-gate impacts of ¾ inch pipe systems.

Only the raw material impacts will change in this sensitivity analysis, as energy inputs are assumed to not change per 1 m of extrusion. Another assumption and limitation is that depending on the pipe wall width, the formulation may differ to maintain pipe integrity, elasticity, or other functionalities which must be preserved.

As seen in **Figure 4-4**, all impact categories and PED indicator are substantially affected by the increase and decrease of pipe wall width. This is expected because the raw material phase of the life cycle was found to be the most significant contributor in all categories (**Figure 4-2**). Thus, adjusting the amount of raw material entering the system will invariably have a large influence on the impacts. While all categories have similar sensitivities, according to **Figure 4-4**, Eutrophication potential is affected the least by changes to pipe wall thickness while Primary Energy Demand is the most affected. Note that this LCA uses the SDR 7.4 product, and all other SDR's are larger, which would reduce the wall thickness for any given pipe size.

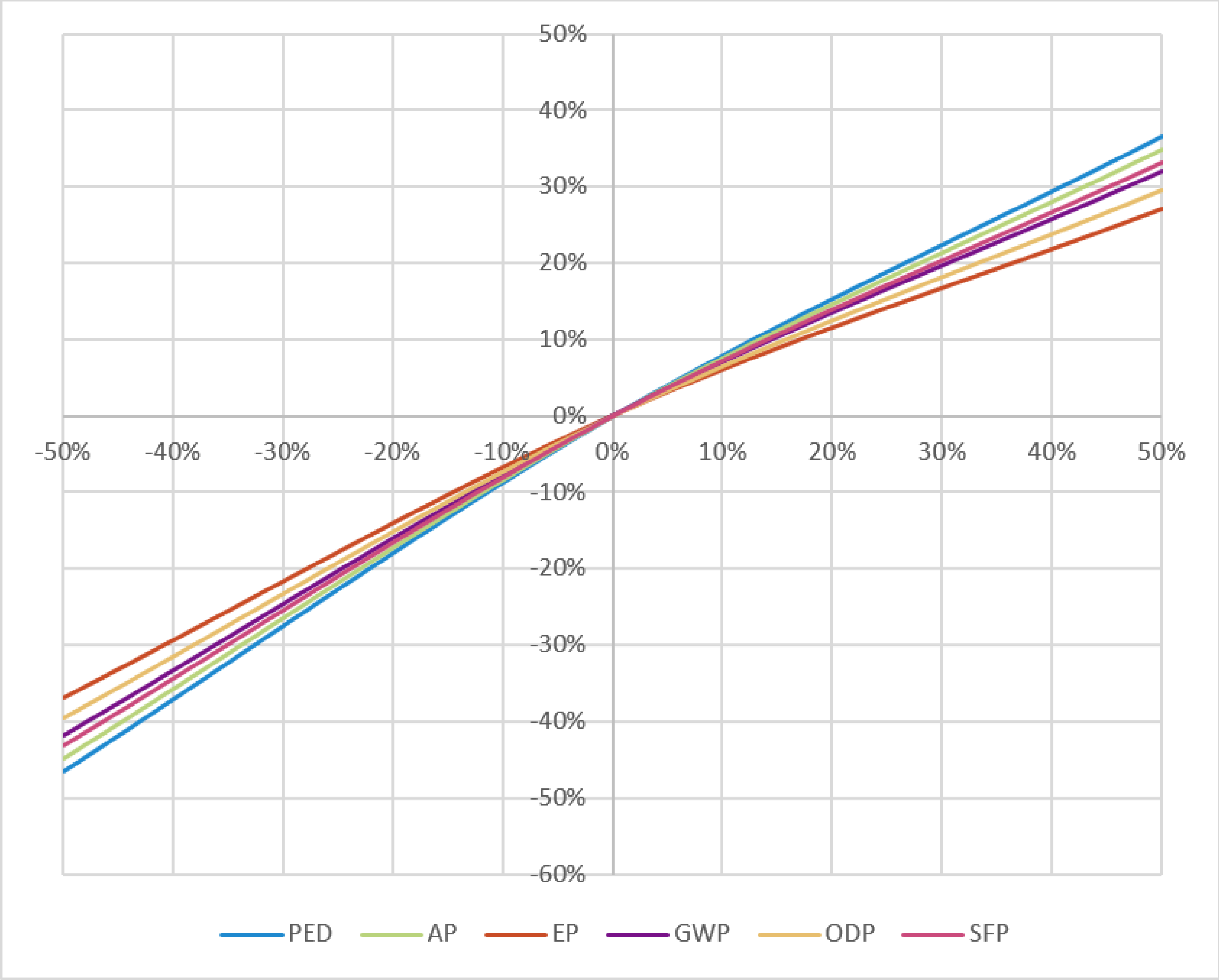

Figure 4-4: Parameter sensitivity – pipe wall variability.

4.4. Scenario Analysis

The average, representative piping system is comprised of five individual piping systems: Green, Blue, Red, Lilac, and Black. The five piping systems all have slightly varying formulation; therefore, scenario analysis is done for the five systems for TRACI 2.1 and PED categories. All five systems were analyzed based on equivalent outer pipe diameter (25 mm) and pipe wall thickness of 3.47 mm.

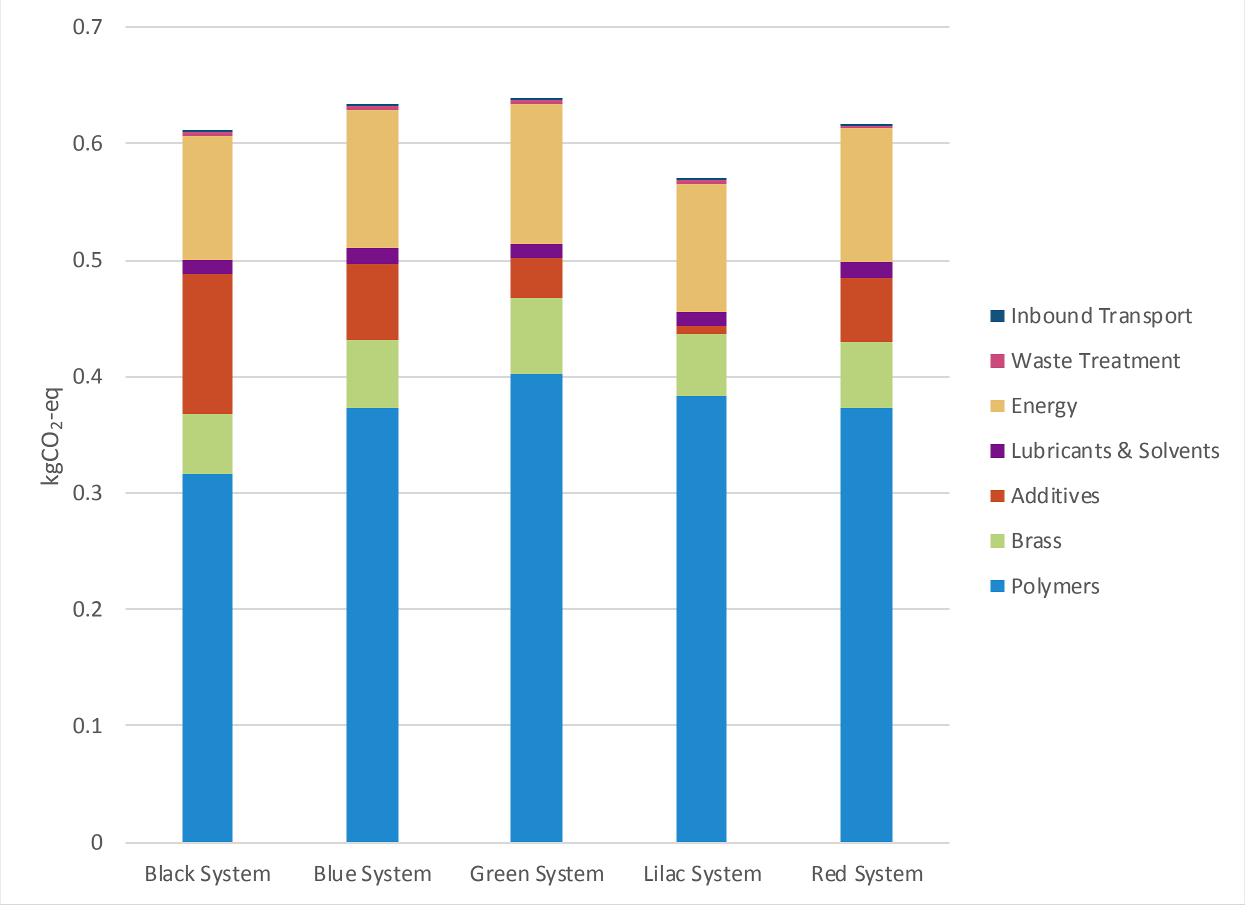

Figure 4-5: Global Warming Potential impact of the five piping systems

As noted previously, the Black System has a unique oxygen barrier layer. However, as shown in Figure 4-5, per 1 m of piping system the presence of the oxygen barrier (in “Additives” category) displaces some of the primary polypropylene input. Lilac System has minimal additives which leads to an overall lower impact for this grouping. All other groupings besides polymers, metals, and additives are expected to be equivalent per 1 m of piping system.

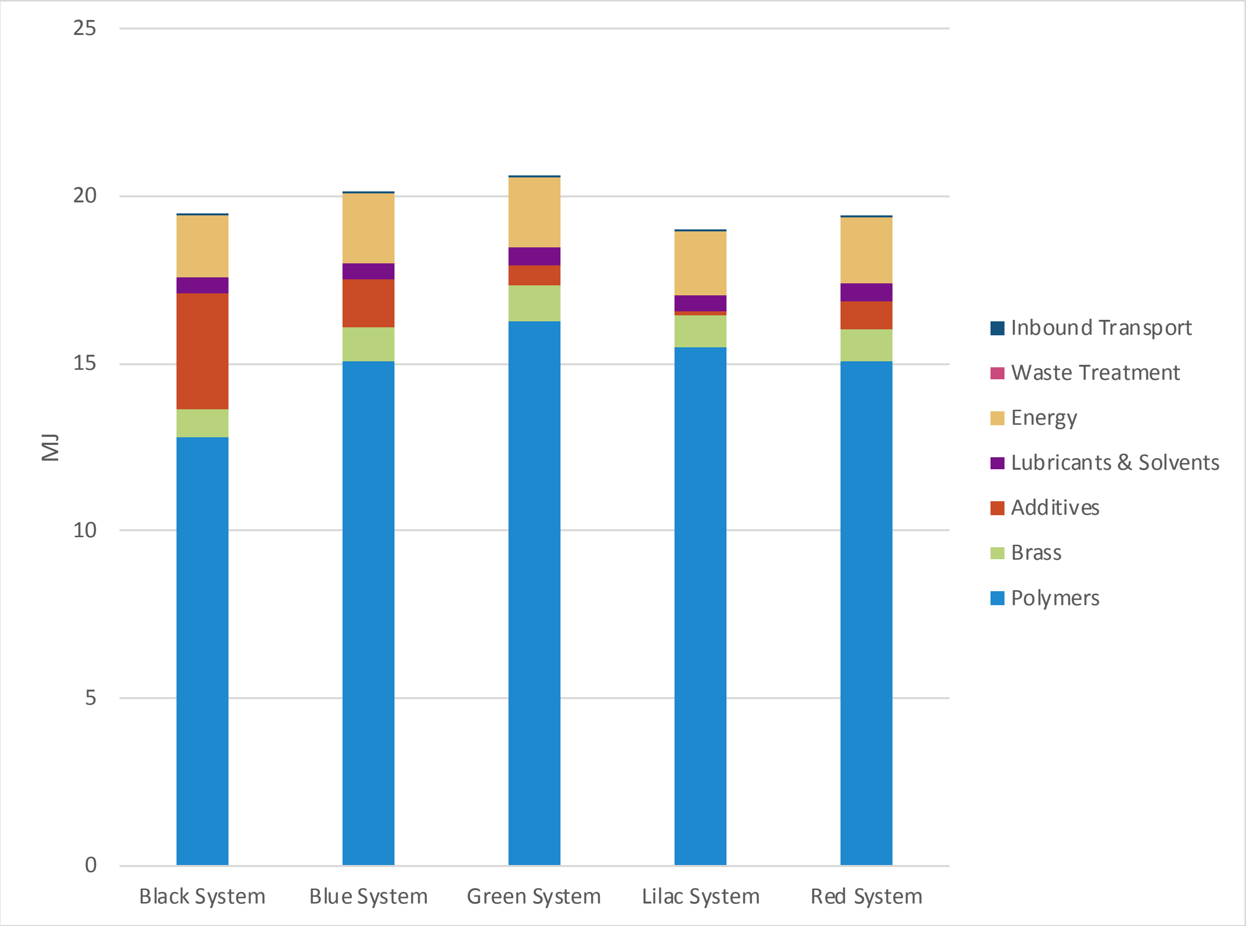

Figure 4-6: Primary Energy Demand indicator of the five piping systems

The PED indicator largely mirrors that of the GWP impacts. Polymers are dominant contributors due to the embodied energy from the naptha and natural gas input feedstock, rather than consumption of energy. Similarly, the oxygen barrier, comprised of polyvinyl alcohol (Table 5-1), is a significant contributor to PED for the Black System. Note that the PED from polymer come from both embodied energy in the polypropylene as well as the energy consumed in its production. The GaBi LCI dataset shows that 55% of the PED of polypropylene come from the embodied energy of the naphtha feedstock, while the remaining 45% come from the energy for production.

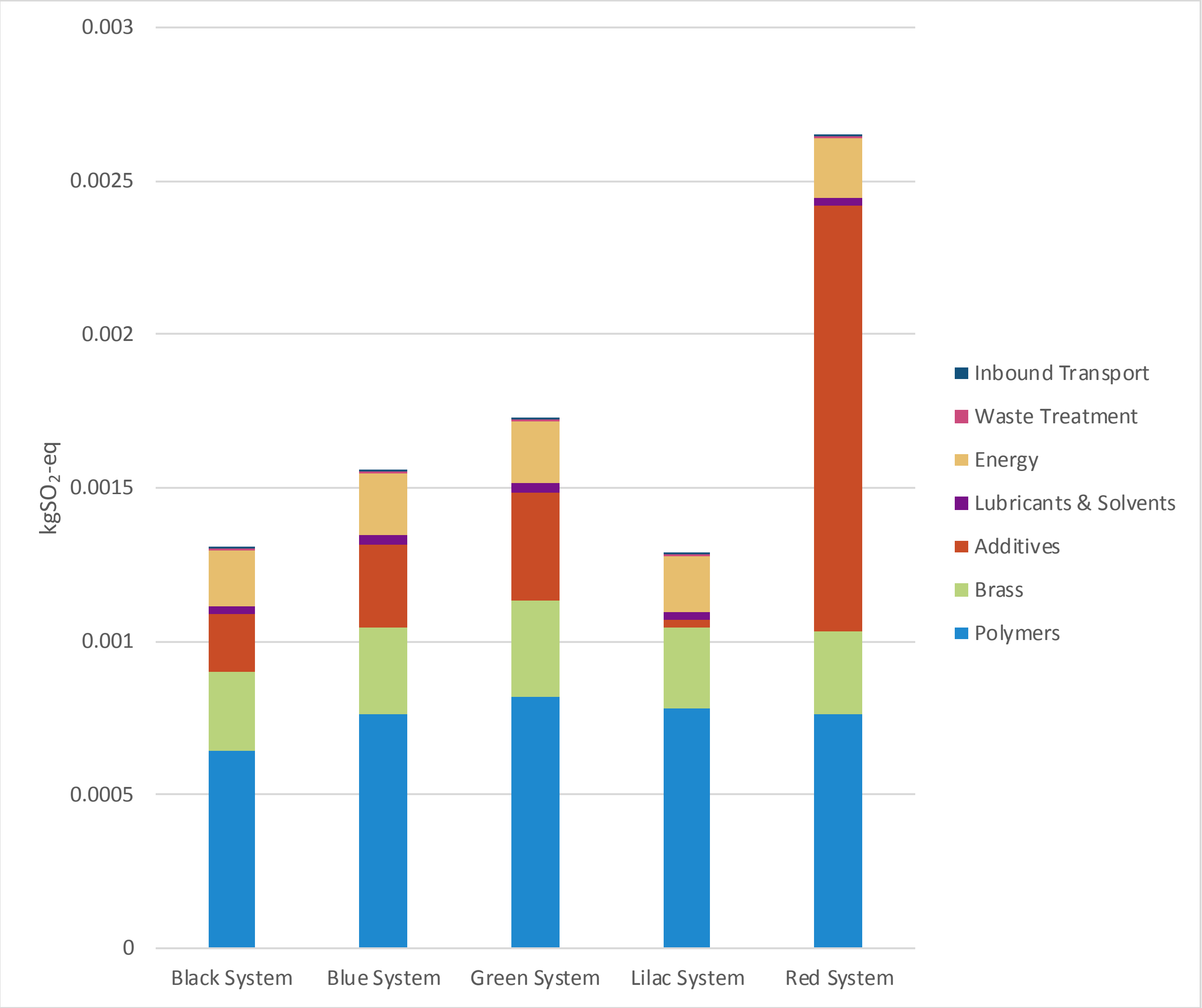

Figure 4-7: Acidification Potential impact of the five piping systems

Polymers, metals, and additives are the main contributors to Acidification Potential for all piping systems. Red System in particular has prominent impacts from additives. The flame retardant, antimony trioxide, is the primary contributor to the high impact for the Red System due to high emissions of sulphur dioxide in its upstream production.

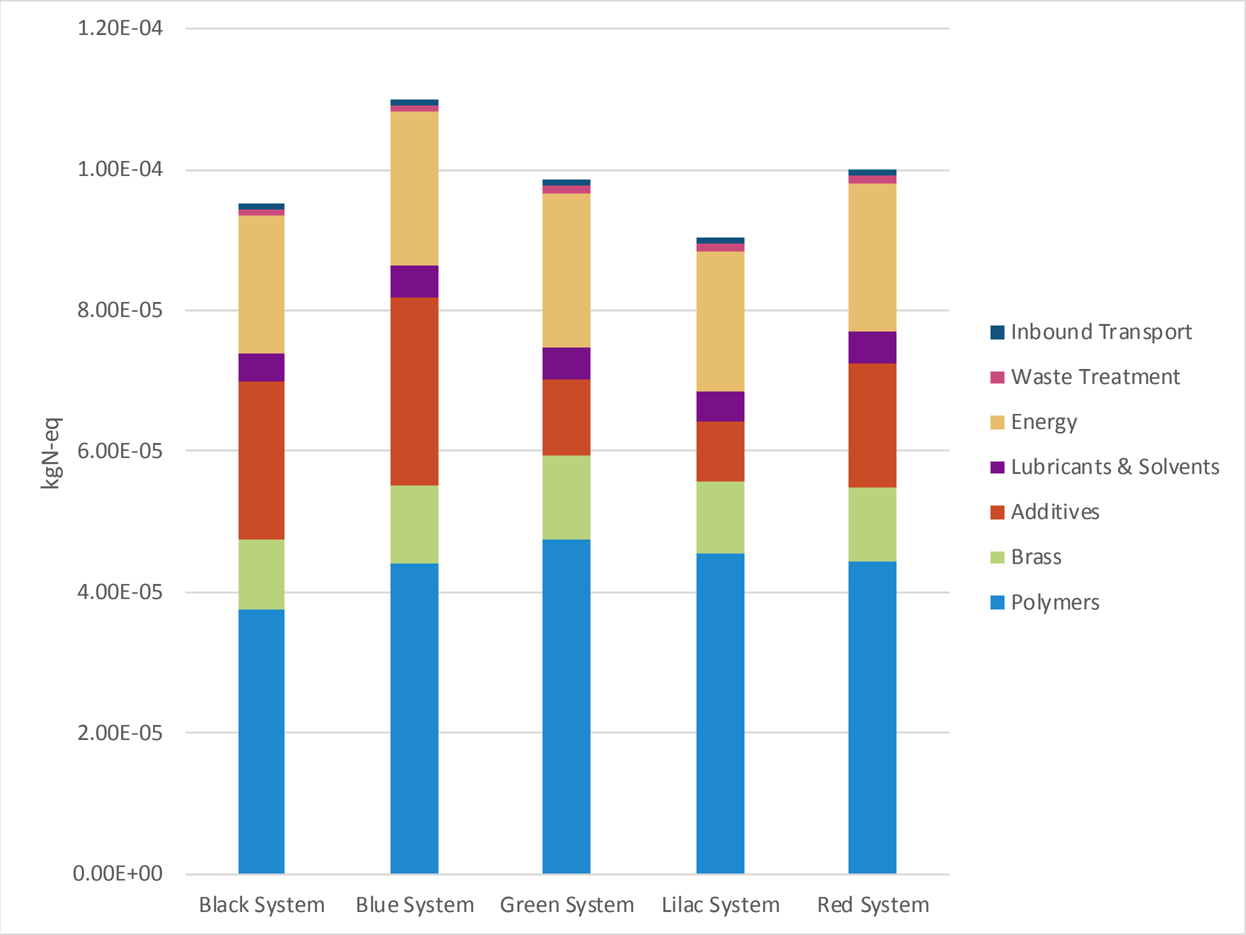

Figure 4-8: Eutrophication Potential impacts of the five piping systems

Polymers, additives, energy, and water inputs are the significant contributors to Eutrophication Potential. All piping systems have Eutrophication impacts from the German electricity grid mix. The impacts from additives come from the glass fiber production in the Blue, Green, and Red System. The oxygen barrier utilized for the Black System has EP impacts.

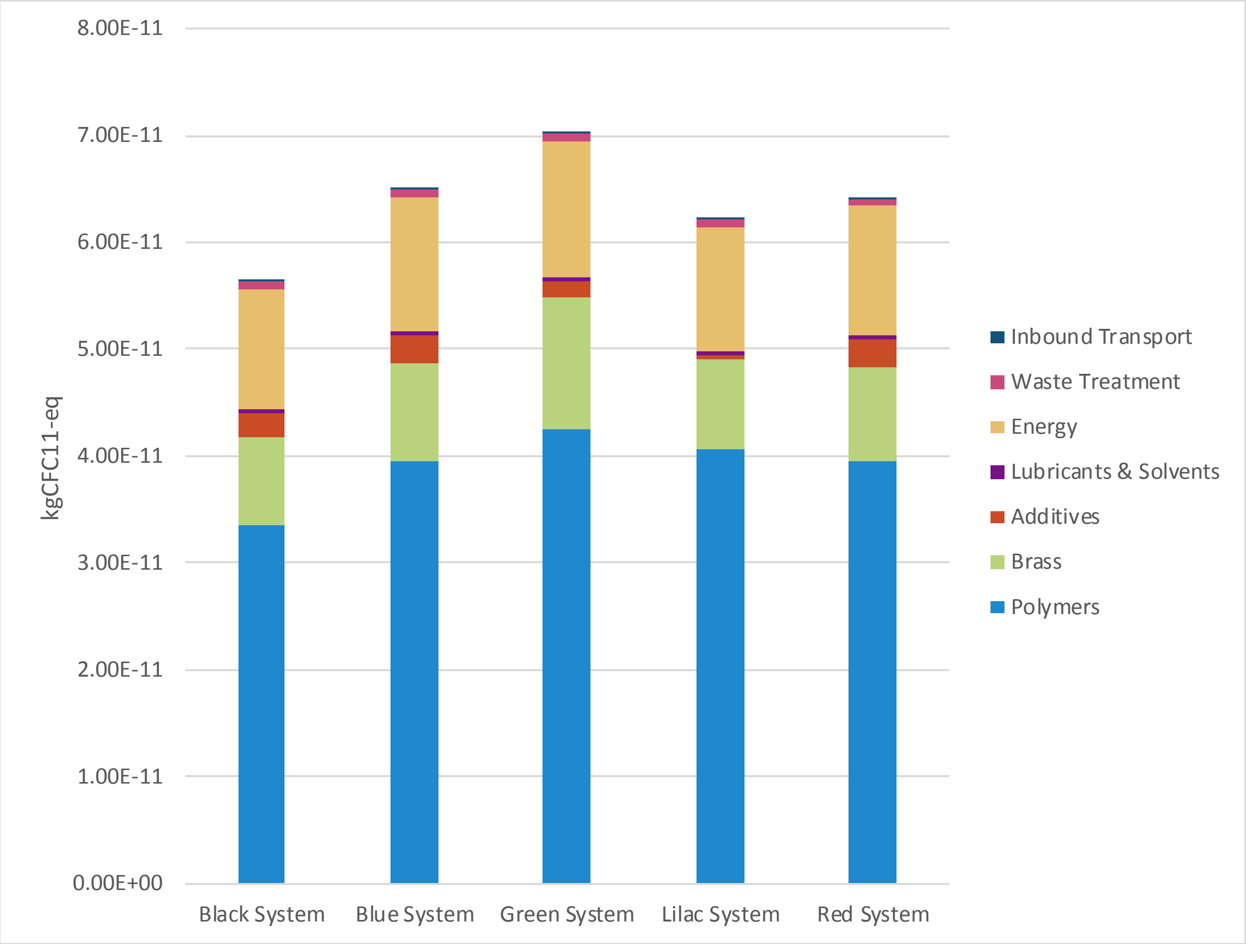

Figure 4-9: Ozone Depletion Potential impacts for the five piping systems

Ozone depletion potentials show that most of the impacts originate from the production of plastics from petroleum. Metal production and provision of energy to the Aquatherm facility are also contributors to ODP.

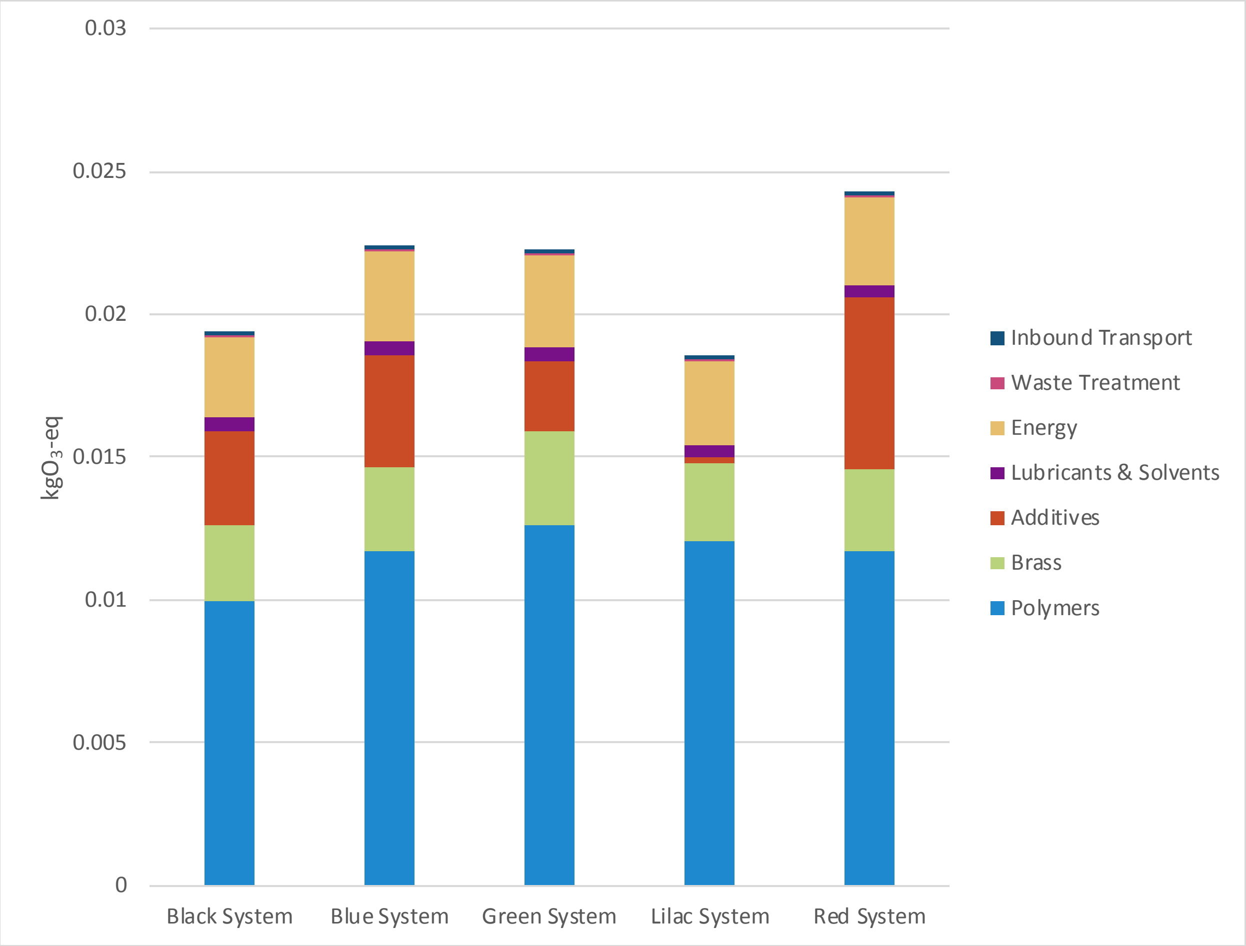

Figure 4-10: Smog Formation Potential impacts for the five piping systems

Polymers, metals, additives, and energy production again are the significant contributors. Glass fibers contribute to SFP impact for Blue, Green, and Red systems. Moreover, the flame retardant in the red pipe (antimony trioxide) also contributes to SFP.

5. Interpretation

5.1. Identification of Relevant Findings

Polypropylene is the primary contributor to all LCIA categories as well as the PED indicator. Additives, metal components, and energy production are significant contributors to all impacts. Depending on the piping system, there are glass fiber reinforcement, oxygen barriers, and other piping system-unique formulations that lead to high impact contributions, which is reflected in the average, representative piping system. Overall, raw materials were the highest impact grouping in the cradle-to-gate analysis.

The impact contribution largely correlated with mass. Polypropylene, brass components, and glass fiber reinforcement overall were the highest impact raw material inputs. The oxygen barrier in the Black System tended to be particularly impactful for Global Warming Potential and Primary Energy Demand for this system. The antimony trioxide flame retardant in the Red System was particularly impactful for Acidification Potential for this system. Because the Lilac System contained minimal additives in its formulation, it was generally the lowest impact piping system.

5.2. Assumptions and Limitations

The average piping system assessed in this study is calculated based on a non-weighted average of five piping systems and considered to be representative. Depending on the piping system, there are unique materials, such as oxygen barrier for the Black System, that are absent in the other systems. Any formulation unique to an individual piping system is less pronounced due to this calculation decision.

Pigments and stabilizer additives are proxies based on CAS numbers provided by Aquatherm and matched with GaBi datasets according to internal expertise. Due to lack of process-specific energy data, electricity consumption includes overhead such as lighting, office, and computers. Any variability in electricity requirement for piping systems is not captured. Polypropylene and metal scrap sent to recyclers are assumed to be recycled into secondary materials which can displace the production of primary materials. This aspect of the life cycle is captured through system expansion.

In the sensitivity analysis, pipe wall thickness was altered to gauge its influence on cradle-to-gate impacts. However, only the total mass was adjusted, with individual components scaled linearly. There may be some need for minor formulation adjustments to maintain the processability of the pipes as sizes and SDR are changed.

5.3. Results of Sensitivity and Scenario Analyses

5.3.1. Sensitivity Analysis

Sensitivity analyses were performed to test the sensitivity of the results towards changes in parameter values that are based on assumptions or otherwise uncertain. The analyses showed that adjusting pipe wall thickness affects the amount of material needed per declared unit and therefore has a substantial, positive correlation to cradle-to-gate impacts for all TRACI 2.1 categories and Primary Energy Demand. This was expected because the Raw Materials grouping was shown to be the dominant contributor for all categories. All categories were generally equally sensitive to adjusting of pipe wall thickness.

5.3.2. Scenario Analysis

Scenario analysis was performed to compare results between different sets of assumptions or modeling choices. The analyses showed that polypropylene dominated overall impact categories. However, depending on the formulation, certain material groupings were particularly impactful for LCIA categories. The antimony trioxide flame retardant in the Red System was particularly impactful for Acidification Potential. The oxygen barrier in the Black System, comprised of polyvinyl alcohol, was impactful for Global Warming Potential and Primary Energy Demand.

5.4. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2015 database were used. The LCI datasets from the GaBi 2015 database are widely distributed and used with the GaBi 6 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.4.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources from Aquatherm, precision is considered to be high. Seasonal variations were balanced out by using yearly aggregate data. All background data are sourced from GaBi databases with the documented precision.
- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi databases with the documented completeness.

5.4.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches.

5.4.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2014. All secondary data come from the GaBi 2015 databases and are representative of the years 2010-2014. As the study intended to compare the product systems for the reference year 2014, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- ✓ **Technological:** All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.5. Model Completeness and Consistency

5.5.1. Completeness

All relevant process steps for each product system were considered and modeled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regard to the goal and scope of this study.

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by exclusively using LCI data from the GaBi 2015 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6. Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

Overall, it was found that the cradle-to-gate impacts largely correlated with the mass input of the formulation. Polypropylene was shown to be the most impactful material input. Brass fittings and glass fibers were also significantly impactful in the average, representative piping system. Although the average piping system diminishes any formulation unique to individual piping system, overall it was found to not influence the main conclusions. The most significant raw materials are supported by material-specific GaBi LCI datasets; therefore, the reported results and conclusions are considered to be robust. Thus, there will be high confidence in reporting the parameters in the Environmental Product Declaration, as required by the guiding PCR.

This study identifies the main drivers of impact for Aquatherm; significant contributors are analyzed at the cradle-to-gate level as well as at the individual material input level. This granular level of reporting will support Aquatherm in continuing to identify key opportunities for improving manufacturing of the piping system.

5.6.2. Limitations

As this study and the associated EPD is a cradle-to-gate analysis, it does not support comparative assertions with LCAs or EPDs with a cradle-to-grave system boundary. Moreover, the LCIA results reported in this study are not comparable with LCAs based on different PCRs.

While the scenario analysis explores the impacts of the individual piping systems, it should not be considered an explicit comparison among piping systems.

5.6.3. Recommendations

Ideally, process-level energy consumption data should be obtained. Moreover, any difference in energy requirements for the different piping system should be captured. The robustness of the conclusions should be tested by collecting formulation and energy consumption data for the individual piping system and their entire range of pipe sizes and SDR offering.

At the Aquatherm facility, energy consumption is the main process which can be controlled. Therefore, there should be continued investigation into improvement opportunities for energy efficiencies. Introduction of recycled materials should be explored as well, although most codes and standards do not allow this for these systems and applications at this time. Currently, the formulation is comprised solely of primary polypropylene. Incorporation of recycled materials would directly lead to displacement of primary polypropylene, which will have a direct correlation to impact reduction.

Following this cradle-to-gate study, a cradle-to-grave study is recommended to assess the environmental performance of Aquatherm piping systems at post-manufacturing stages. The guiding PCR supports cradle-to-grave declarations; therefore, the system boundary can be expanded while leveraging this initial study.

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Annex A

Table 5-1: Key material datasets used in Aquatherm inventory analysis

Aquatherm Material / Process	Dataset	Data Provider	Reference Year	Geographic Reference
Polypropylene	Polypropylene granulate (PP) mix	thinkstep AG	2013	Germany
Polyethylene, high density	Polyethylene High Density Granulate (HDPE/PE-HD)	thinkstep AG	2012	Germany
Polyethylene, low density	Polyethylene Low Density Granulate (LDPE/PE-LD)	thinkstep AG	2013	Germany
Nylon	Polyamide 6.6 Granulate (PA 6.6) Mix	thinkstep AG	2013	Germany
Polyphenylene sulfide	Polyphenylene sulfide granulate (PPS)	thinkstep AG	2013	Germany
Aluminum	Aluminium part	thinkstep AG	2013	EU-27
Stainless steel	stainless steel parts turned	thinkstep AG	2012	Germany
Aluminum part	Aluminium foil	thinkstep AG	2012	EU-27
Brass fitting	Brass die-casting (CuZn20)	thinkstep AG	2012	Germany
Oxygen barrier	Polyvinyl alcohol granulate (PVAL)	thinkstep AG	2013	Germany
Glass fibers	Glass fibres	thinkstep AG	2013	Germany
Flame retardant	Antimony trioxide	thinkstep AG	2013	EU-27
Adhesive		thinkstep AG		
	Polyalphaolefine over 1-Decen (PAO) *	thinkstep AG	2012	Germany
	Maleic anhydride*	thinkstep AG	2013	Germany
Antioxidizing agent				
	Diethyl ether*	thinkstep AG	2012	Germany
	Phenol*	thinkstep AG	2012	Germany
	Acrylic acid (Propene)*	thinkstep AG	2013	Germany
Phosphite stabilizer	Tris (chloro-ethyl) phosphate*	thinkstep AG	2012	Germany
Heat stabilizer	Bariumstearate (stabilizer, estimation)*	thinkstep AG	2012	EU-27
Metal deactivator	Hydrazine hydrate/hydrazine*	thinkstep AG	2012	Germany
Magnesium oxide	Magnesium oxide (MgO, fine, filler)	thinkstep AG	2012	Germany
Black pigment	Carbon black (furnace black; deep black pigment)	thinkstep AG	2013	Germany
Violet pigment	Carbazole Violet (estimate)*	thinkstep AG	2012	United States
Blue pigment	Aluminium silicate (zeolite type A)*	thinkstep AG	2012	Germany
Blue pigment	Copper phthalocyanine (estimation)	thinkstep AG	2012	Germany
Green pigment	Copper phthalocyanine (estimation)	thinkstep AG	2012	Germany
Red pigment				
	Diethanolamine (DEA)*	thinkstep AG	2013	United States
	C12-C14-Mono glycidyl ether (estimation)*	thinkstep AG	2012	Germany
Red pigment				
	Aniline (Phenyl amine, Amino benzene)*	thinkstep AG	2013	Germany

Aquatherm Material / Process	Dataset	Data Provider	Reference Year	Geographic Reference
	Chlorobenzene (by product chlorobenzene, hydrochloric acid)*	thinkstep AG	2012	Germany
Yellow pigment				
	Chrome concentrate*	thinkstep AG	2012	Global
	Titanium dioxide pigment (sulfate process)*	thinkstep AG	2012	Germany
	Antimony*	thinkstep AG	2013	China
Zinc sulfide				
	Zinc oxide	thinkstep AG	2012	Germany
	Hydrogen Sulfide	thinkstep AG	2012	EU-27
MEK	Methyl ethyl ketone (2-butanone, MEK)	thinkstep AG	2012	Germany
Decahydronaphthalene	Naphtha at refinery*	thinkstep AG	2011	Germany
Dilutant				
	Ethyl acetate	thinkstep AG	2012	Germany
	Butyl acetate	thinkstep AG	2012	Germany
	p-Xylene (from reformate)	thinkstep AG	2013	Germany
	Toluene	thinkstep AG	2012	Germany
	Butane	thinkstep AG	2013	Germany
Solvent				
	Acetone	thinkstep AG	2013	Germany
	Methyl ethyl ketone (2-butanone, MEK)	thinkstep AG	2012	Germany
Printing ink				
	Methyl ethyl ketone (2-butanone, MEK)	thinkstep AG	2012	Germany
	Acetone	thinkstep AG	2013	Germany
Corrugate box	Average corrugated board box (paper/cardboard)	thinkstep AG	2011	EU-27
Pallets	Wooden pallets (EURO, 40% moisture)	thinkstep AG	2012	EU-27
Lumber	Timber spruce (65% moisture)	thinkstep AG	2013	Germany
Plastic film	Polyethylene Film (PE-LD) without additives	thinkstep AG	2013	Germany

* indicates dataset used is a proxy for the Aquatherm material/process