UniTech Services Group

Comparative LCA of Protective Garments

Comparing life cycle impacts of a reusable protective garment set to a disposable protective garment set in radioactive material applications

10/18/2013

PE INTERNATIONAL

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SUSTAINABILITY PERFORMANCE

On behalf of PE INTERNATIONAL AG and its subsidiaries

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ACRONYMS

AP	Acidification Potential
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GWP	Global Warming Potential
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
PE	PE INTERNATIONAL
POCP	Photochemical Ozone Creation Potential
VOC	Volatile Organic Compound

GLOSSARY (ISO 14040/44:2006)

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva.

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

Functional Unit

Quantified performance of a product system for use as a reference unit

Close loop & open loop

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.

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.

Cradle to grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life.

Cradle to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process (“gate of the factory”). It may also include transportation until use phase.

Gate to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) only within the production process (“gate of the factory”).

Life cycle

A unit operations view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated 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

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.

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

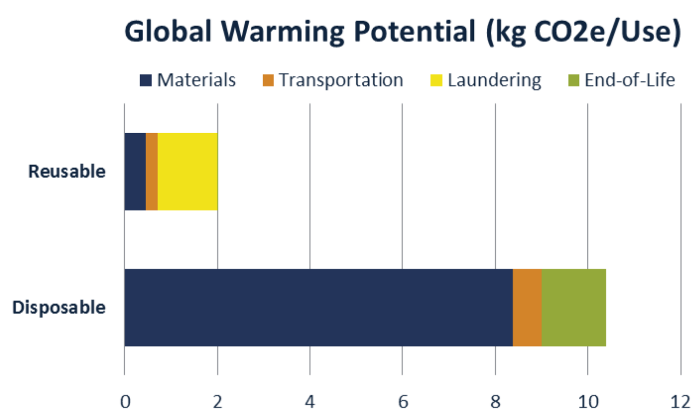
Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

EXECUTIVE SUMMARY

UniTech commissioned PE INTERNATIONAL, Inc. to compare the environmental performance of a reusable protection suit with a disposable suit alternative. As the results of this comparison will be used for external communication, and will support comparative assertions**, a critical review panel has been engaged to ensure that the study meets the requirements of the ISO 14044 standard and further strengthen the credibility of these final results.** This study is intended for use by UniTech for distribution to current and potential customers.

The goals of this study were to compare the cradle-to-grave impacts of two garment sets used for low-level radioactive particulate contamination protection and contamination control purposes. A garment set includes the following: coveralls, hood, shoe covers, rubber gloves, rubber shoes, and a scrub top and bottom[1]. Additionally, the reusable garment set includes a laundry bag that facilitates transport to and from the laundering facility, while the disposable garment set includes a bag that transports the set to final disposal. Primary data was collected from UniTech on laundering and transportation requirements for the reusable garment set. Secondary data from relevant literature was used to model the remaining data requirements. Where a parameter was found to significantly affect the conclusions, a scenario analysis was performed modeling best and worst cases.

The figure below shows the cradle-to-grave Global Warming Potential (GWP) of the two product systems under study, based on the assumption that the reusable garment set is used at least 48 times. In line with all other impact categories assessed in this study, the reusable garment set has a lower impact per use than the disposable garment set alternative, as long as the reusable garment set has at least 4 wearings. In standard usage conditions, the single use PVA garment set has 5 times more carbon impact than the reusable garment set.



[1] Scrubs are shirts and trousers designed to be easy to launder and cheap to replace if damaged. In this case, scrubs are worn under the protective suit.

To improve upon overall environmental impacts, UniTech should focus on the impacts associated with their washing facilities, as this was shown to be the life cycle stage with the largest contribution to the total environmental burden.

1 GOAL OF THE STUDY

UniTech, a radiological laundering and protective clothing provider, seeks to understand the environmental performance of its products. To achieve this goal, UniTech has engaged PE INTERNATIONAL, Inc. (PE) to conduct a comparative life cycle assessment. This will enable UniTech to demonstrate sustainability leadership and leverage business value.

The goal of this study is to compare the "cradle-to-grave" environmental performance of a launderable protective garment set with a disposable set alternative. UniTech's primary reasons for carrying out this study are to:

- understand the life cycle impacts of their product,
- understand how their product compares to the single-use alternative, and
- use the resulting LCA information to inform their marketing and operating strategies.

The intended audience for this report is both internal and external. Internally it will be used by marketing, R&D, facilities management, and executives within UniTech. Externally, the results will be communicated to current and potential customers through marketing initiatives. This report will be used to support and reinforce any marketing assertions made.

The intent of this study is to make a comparison; as such, it will be used for comparative assertions disclosed to the public about the environmental superiority of one product over another.

2 Scope of the Study

The following section describes the general scope of the project to achieve the stated goals. This includes the identification of specific products to be assessed, their functional unit, the system boundary, allocation procedures, and cut-off criteria.

2.1 Product System(s) to be studied

This study will evaluate two types of protective garment sets used to prevent low-level radioactive particulate contamination, reusable and disposable. These suits are primarily required when nuclear power plants undergo maintenance activity during shutdown periods. The term 'set' refers to the combination of a coverall, hood, pair of shoe covers, pair of gloves, pair of rubber boots, scrub top, and scrub bottom. For the reusable garment set the environmental impact includes, for the purposes of assessment, a portion of the laundry bag required for transport to the laundering facility, while the disposable garment set includes the plastic bag required for transport to final disposal.

UniTech typically provides the reusable garment set through a lease program, allowing UniTech to launder and re-distribute the garment for further use. All components of the disposable garment set are purchased, used, and then disposed.

2.2 Product Function(s), Functional Unit and Reference Flows

The primary purpose of the protective garments under study is to prevent and control low-level radioactive particulate contamination. An entire set of garments is defined as including: coverall, hood, shoe covers, rubber shoes, rubber gloves, a scrub top and bottom, and a laundry bag. This study will compare a reusable set and a disposable set of "size: large" garments for the following functional unit:

One wearing event

The reference flow represents the specific systems required to achieve the functional unit. For the disposable garment, this will equate to one set. The reusable garment can be worn multiple times before it reaches its EoL. To account for this, the life cycle was scaled to the functional unit, i.e., a single wearing event, based on the total wearing events that can occur over the lifetime of each component of the reusable garment set. Using RFID tags, UniTech is able to record the reject rate of garments during processing. Combined with the total number of garments processed, this allows for the average number of lifetime uses to be calculated. The total number of wearing events is one more than the number of lifetime processing cycles since the first use does not require prior laundering by UniTech. Values calculated to be greater than 200 were rounded down to 200 for a conservative assessment. A scenario analysis on these values is included in Section 5.3.1. See Table 2-1 for details on the reference flows used.

Table 2-1: Reference flows

Type	Weight of Reusable Garments (*lbs*)	Lifetime Uses	Reusable garment weight scaled by lifetime uses (*lbs*)	Weight of Disposable Garments (*lbs*)
Coverall	1.05	48	2.19E-02	0.67
Hood	0.21	200	1.05E-03	0.07
Shoe covers	0.25	88	2.84E-03	0.13
Shoes	0.53	23	2.30E-02	0.29
Gloves	0.27	9	3.00E-02	0.15
Scrub Top	0.41	200	2.05E-03	0.24
Scrub Bottom	0.38	200	1.90E-03	0.23
Laundry bag	1.47	140	1.05E-02	0.25

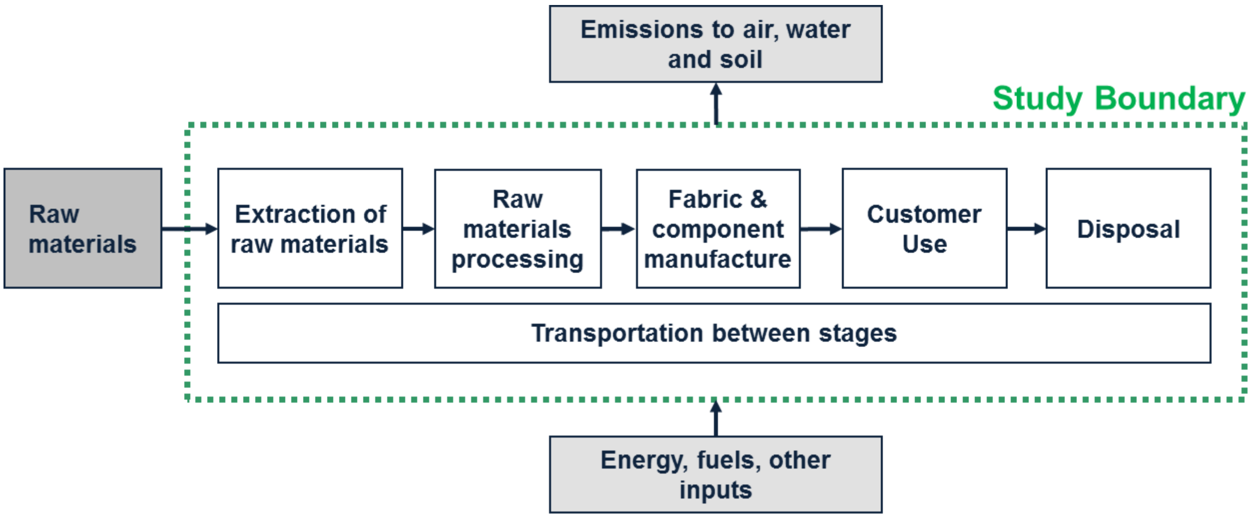
2.3 System Boundaries

The scope of the study includes manufacturing, laundering, and End-of-Life (EoL) treatment, along with the associated transport in and between phases. Table 2-2 summarizes the system boundary for the cradle-to-grave analysis. Overhead, capital equipment construction, and employee commute are excluded, amongst others. Figure 2-1 presents a visualization of the system boundary.

Table 2-2: System Boundaries

Included	Excluded
✓ Raw material extraction ✓ Processing of materials ✓ Energy production ✓ Manufacturing ✓ Transport of raw materials and finished products ✓ Use, including laundering and associated transportation ✓ End-of-Life treatment	× Construction of capital equipment × Employee commute × Overhead × Manufacture and transport of upstream packaging materials × Maintenance and operation of support equipment

Figure 2-1: Study boundary



2.3.1 Time Coverage

Primary data, which refers to information collected directly from UniTech's operations, are representative of the UniTech fiscal year, September 2011 through August 2012. Secondary data, information from relevant literature, are from a range of sources between 1993 and 2012. Background data, upstream information necessary to model material production, energy use, etc., was adopted from PE's GaBi 2012 database and is described further in Chapter 3.

2.3.2 Technology Coverage

UniTech provides radiological laundering and protective clothing services. Data were collected from UniTech on laundry facility operations, associated transportation requirements, and protective garment specifications. The disposable protective garment set, excluding the gloves and boots, is made of hot water soluble polyvinyl alcohol (PVA) non-woven fabric and film. Data on the associated manufacturing and dissolution processes were obtained from relevant literature [Eden 2012, Honeycutt 1993, Honeycutt 1999, Langley 1999, Oji 1999, Eastern Technologies 2010, Yang et al. 1997]. Secondary data comes from the PE database.

2.3.3 Geographical Coverage

The region under study for the use phase is the United States of America. Manufacturing of the fabric components of the disposable garment set and portions of the reusable garment set occurs in China, with the remaining reusable garment fabric manufacturing occurring in the mid-Atlantic US. Rubber shoes and gloves are manufactured in Taiwan and China, respectively, for both garment sets.

2.4 Allocation

To evaluate the reusable garment for a single wearing event, the material manufacturing and EoL impacts had to be scaled based on the number of wearing events possible over the lifetime of the garment; that is, until the individual components had to be disposed of. This value varies for each component of the garment set. For example, a rubber glove can be used far fewer times than a hood before it can no longer fulfill its intended function. A scenario analysis is included in Section 5.3.1 to address the effect the number of lifetime uses has on the final conclusion.

The impact of the laundry bags are allocated to each use of the respective garment set by mass, according to the portion of the bag capacity utilized. It is then further allocated by the number of lifetime uses for the reusable set.

Laundering operations at the UniTech facilities considered were allocated by weight of material processed over the specified time period, i.e., per pound of garment laundered.

Allocation of upstream, background data (energy and materials):

- ✓ For all refinery products, allocation by mass and net calorific value is applied. The manufacturing route of every refinery product is modeled and so the effort of the production of these products is calculated specifically. Two allocation rules are applied: 1. the raw material (crude oil) consumption of the respective stages, which is necessary for the production of a product or an intermediate product, is allocated by energy (mass of the product multiplied by the calorific value of the product); and 2. the energy consumption (thermal energy, steam, electricity) of a process, e.g. atmospheric distillation, being required by a product or an intermediate product, are allocated to the product according to the share of the throughput of the stage (mass allocation).
- ✓ Materials and chemicals needed during manufacturing are modeled using the allocation rule most suitable for the respective product. Further information on specific allocation methods applied to background data can be provided upon request.

2.5 Cut-Off Criteria

No cut-off criteria were applied in this study. All reported data was incorporated and modeled using best available LCI data. For use of proxy data, see Section 2.8.

2.6 Selection of LCIA Methodology and Types of Impacts

A set of impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-3. TRACI 2.1 was selected as it is currently the only impact assessment methodology framework which incorporates US average conditions to establish characterization factors [Bare 2010, EPA 2012]. Table 2-4 shows the other environmental inventory indicators calculated in this study.

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 times.

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 political relevance, which eventually led to the worldwide ban of more active ozone-depleting substances, with the phase-out of less active substances to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear power production. In addition, the slash-and-burn of field crops is also known to result in relevant emissions of ozone-depleting substances. The indicator is therefore included for reasons of completeness.

Water consumption, i.e., the man-made removal of water from its watershed through shipment or evaporation, 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. The use of treated water also leads to impacts in other categories, such as global warming potential and eutrophication, which are included in the analysis.

Table 2-3: TRACI 2.1 Impact Assessment Descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP)	A measure of greenhouse gas emissions, such as CO2 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	[Bare 2010], [EPA 2012]
Eutrophication Potential (EP)	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which are 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 Nitrogen equivalent	[Bare 2010], [EPA 2012]
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	[Bare 2010], [EPA 2012]
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O3), 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	[Bare 2010], [EPA 2012]

Impact Category	Description	Unit	Reference
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	[Bare 2010], [EPA 2012]

Table 2-4: 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)	An operational guide to the ISO-standards (Guinée et al.) Centre for Milieukunde (CML), Leiden 2001.
Life Cycle Inventories of Water Inputs/Outputs	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 scarcity.	kg of water	GaBi 6 Software database

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 emitted molecules 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 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.

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 is considered to be of the highest *precision*, followed by calculated and estimated data from secondary sources.
- *Completeness* is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. Cut-off criteria apply and were defined in Chapter 2.5.

- *Consistency* refers to modeling choices and data sources. The goal is to ensure that differences in results occur due to actual differences between product systems, and not due to inconsistencies in modeling choices, data sources, emission factors, or other.
- *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 the interpretation chapter of this report.

2.8 Assumptions and Limitations

Data used to represent the disposable garment set were taken from publically available information from a participant in the market for this type of garments. As their material, manufacturing, and dissolution processes are proprietary information, lower values were assumed when modeling the disposable garment. The material formula is based on US Patent No. 5,658,977 (Yang et al. 1997), which uses an 88% partially hydrolyzed PVA. Data on PVA was only available for a fully-hydrolyzed process; as such, the energy required was modified assuming the hydrolysis process scales linearly with degree of hydrolysis. A scenario analysis on the impact of the degree of hydrolysis on the final conclusion is presented in Section 5.3.2. So even if the assumptions are inaccurate,, the study serves to bound the potential impacts.

When PVA is dissolved in hot water—using hydrogen peroxide and an iron catalyst—it releases carbon dioxide. The rate of emission is calculated based on reaction stoichiometry and existing data on EoL processing [Oji 1999]. Because the precise processing conditions are also proprietary, assumptions had to be made and conservative values were used whenever possible. Assumptions were based in part on the proprietor's claims, e.g., that the only byproducts of PVA dissolution are CO_2 and water. Process emissions were only calculated for the weight of PVA being disposed of, while the rubber shoes and gloves were incinerated. See Section 3.3.1.3 for further information.

Due to data availability, cut-and-sew energy use and material losses were excluded from the study for both reusable and disposable garment sets. It is assumed that the energy use for the initial cut-and-sew manufacturing of both the disposable and reusable garment sets would be similar, though per use it would decrease for the reusable set, as it would be distributed over the possible lifetime uses. Additionally, the potential impacts from cut-and-sew are believed to be minor compared to the actual manufacturing of the material; therefore, it is anticipated that this limitation will not change the overall conclusions.

The ProTech and CoolTech fabrics used in the reusable garment set are specified as 99% nylon and PET, respectively, and 1% carbon fiber. This carbon fiber, however, is a bicomponent yarn that is less than 10% by mass carbon fiber. Due to this low fraction of carbon fiber, and to lack of available data on the manufacturing process of the type of carbon fibers used by these products, the ProTech and CoolTech fabrics were assumed to be 100% nylon and PET, respectively.

2.9 Software and Database

The LCA model was created using the GaBi 6 Software system for life cycle engineering, developed by PE INTERNATIONAL AG. The GaBi 2012 LCI databases provide the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.10 Critical Review Panel Statement

Review of the Report "Comparative LCA of Protective Garments" (Dated October 17, 2013), Conducted for UniTech Services Group by PE International & Five Winds Strategic Consulting

Review Statement Prepared by the Critical Review Panel:
Arpad Horvath (Chair), John M. Smith, Donald B. Thompson

October 18, 2013

The review of this report has found that:

- the approach used to carry out the LCA is consistent with the ISO 14040:2006 principles and framework and the ISO 14044:2006 requirements and guidelines,
- the methods used in the LCA appear to be scientifically and technically valid,
- the interpretations of the results reflect the limitations identified in the goal of the study,
- the report is transparent concerning the study steps and consistent for the purposes of the stated goals of the study.

This review statement only applies to the report named in the title, available to the Critical Review Panel on September 9, 2013, but not to other versions, excerpts, press releases, and similar derivative reports.

John M. Smith
Consultant, Textile Industry

Arpad Horvath
Consultant, Berkeley, California

Donald B. Thompson
Research Professor, North Carolina State University

3 Life Cycle Inventory (LCI) Analysis

3.1.1 Data Collection & Quality Assessment Procedure

All primary data were obtained from UniTech and secondary data came from literature. Upon receipt, each source of data was cross-checked for completeness and plausibility using mass balance, stoichiometry, and benchmarking. If gaps, outliers, or other inconsistencies occurred, PE engaged with the data provider to resolve any open issues.

3.1.2 Fuels and Energy – Background Data

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 6 database 2012. Table 3-2 shows the relevant LCI datasets used in modeling the product systems. The Chinese electricity grid mix data set is 78% hard coal and is based on 2009 data.

Table 3-1: Key energy datasets used in inventory analysis

Energy	Dataset name	Primary source	Year	Geography
Electricity	Electricity grid mix (East)	PE	2009	US
Electricity	Electricity grid mix	PE	2009	US
Electricity	Electricity grid mix	PE	2009	CN
Thermal Energy	Thermal energy from natural gas	PE	2009	US
Thermal Energy	Thermal energy from hard coal	PE	2009	CN
Truck Fuel	Diesel mix at refinery	PE	2009	US
Ship fuel	Heavy fuel oil at refinery (0.3wt.% S)	PE	2009	US
Steam	Process steam from natural gas 90% eff.	PE	2009	US

3.1.3 Materials and Processes – Background Data

Data for up- and downstream raw materials and unit processes were obtained from the GaBi 6 database 2012. Table 3-2 and Table 3-3 show the most relevant LCI datasets used in modeling the product systems. Documentation for all datasets can be found at www.gabi-software.com/support/gabi/gabi-6-lci-documentation.

Table 3-2: Material datasets used in Reusable and Disposable garment sets' life cycles

Material	Dataset name	Primary source	Year	Geography
Rubber	Styrene-butadiene rubber	PE	2011	US
Water	Water deionized	PE	2011	US
Water	Tap water from groundwater	PE	2011	US
Lubricant	Lubricants at refinery	PE	2009	CN
Nylon	Nylon (PA 6.6) - yarn	PE	2011	US
Nylon	Polyamide 6 Granulate (PA 6)	PE	2011	US

Nylon	Polyamide 6.6 granulate (PA 6.6) (HMDA via adipic acid)	PE	2011	US
Plastic film process	Plastic Film (PE, PP, PVC)	PE	2011	GLO
PVC	Polyvinylchloride granulate (Suspension, S-PVC)	PE	2011	US
PET	Polyethylene Terephthalate Fibres (PET)	PE	2011	US
PVA	Polyvinyl alcohol (from vinyl acetate)	PE	2011	US
Laundry Chemical	n-Methylpyrolidone (NMP, Butyrolactone via Maleic anhydride)	PE	2011	DE
Laundry Chemical	Fluorosilicic acid by-product phosphoric acid (75%) (estimation)	PE	2011	US
Laundry Chemical	Phosphoric acid (highly pure)	PE	2011	US
Laundry Chemical	Dispersing agent (ethoxylate fatty alcohols)	PE	2011	GLO
Laundry Chemical	Propylene oxide (Oxirane process)	PE	2011	US
Laundry Chemical	Sodium sulphate	PE	2011	GLO
Laundry Chemical	Non-ionic surfactant (ethylene oxide derivatives)	PE	2011	GLO
Laundry Chemical	Isopropanol	PE	2011	US
Laundry Chemical	Methyl t-Butylether (MTBE) from C4	PE	2011	US
Laundry Chemical	Aluminium silicate (zeolite type A)	PE	2011	US
Laundry Chemical	Potassium hydroxide (KOH)	PE	2011	US
Laundry Chemical	Trisodium phosphate	PE	2011	GLO

Table 3-3: Disposal datasets

Material	Dataset name	Primary source	Year	Geography
Landfill	Landfilling of plastic waste	PE	2011	US
Landfill	Landfill, arid climate	PE	2011	US
Waste water treatment	Waste water treatment (slightly organic and inorganic contaminated)	PE	2011	EU-27
Incineration	Municipal Solid Waste Incineration	PE	2011	US
Landfill	Landfilling of glass/inert	PE	2011	US
Dissolution Chemical	Hydrogen peroxide (100%; H_2O_2) (Hydrogen from steam reforming)	PE	2011	US

3.1.4 Transportation

Average transportation distances and modes are included for the upstream raw materials coming into production and assembly facilities.

The GaBi data sets for road vehicles and fuels were used to model transportation. Truck transportation within the United States was modeled using the GaBi 6 US truck datasets. The vehicle types, fuel usage, and emissions for these transportation processes were developed using data from the most recent US Census Bureau Vehicle Inventory and Use Survey (2002) and US EPA emissions standards for heavy trucks in 2007. The 2002 VIUS survey is the most current available data describing truck transportation fuel consumption and utilization ratios in the US, and the 2007 EPA emissions standards are considered to be the most appropriate data available for describing current US truck emissions.

3.1.5 Emissions to Air, Water and Soil

Data for all upstream materials, electricity, and energy carriers were likewise obtained from the GaBi 2012 databases. The emissions (CO_2, etc.) due to the use of electricity are accounted for with the use of the database processes.

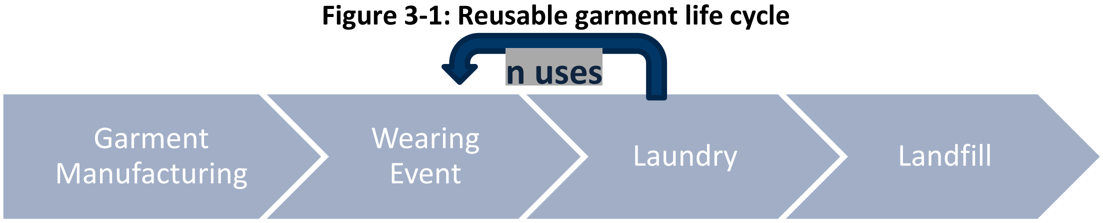
Emissions associated with transportation were determined by capturing the logistical operations of involved companies (data collected from the companies for the reference year). Energy use and the associated emissions were calculated using pre-configured transportation models from the GaBi 6 database 2012.

3.2 Reusable Protective Garment

3.2.1 Overview of Life Cycle

The lifecycle of the reusable protective garment, as seen in Figure 3-1, consists of the manufacturing of each piece of the garment set, the actual wearing event, laundering, and EoL treatment. Transportation between phases is also included. The ‘n uses’, nominally 100 times, represent the cycles of garment use, transport, and washing.

Figure 3-1: Reusable garment life cycle



The reusable garment set consists of a coverall, hood, shoe covers, shoes, gloves, scrubs, and a laundry bag. The coverall and hood are both made of ProTech fabric and the scrub set is made of CoolTech. Both the shoes and gloves are rubber, while the shoe covers and laundry bag are made of nylon fabric. The laundry bag also contains a clear PVC window. Table 3-4 lists the material and associated weight.

Table 3-4: Reusable garment set materials and weights (size: large)

Type	Material	Weight	Unit	DQI
Coverall	ProTech	1.05	lbs	Measured
Hood	ProTech	0.21	lbs	Measured
Shoe covers	Nylon	0.25	lbs	Measured
Shoes	Rubber	0.53	lbs	Measured
Gloves	Rubber	0.27	lbs	Measured
Scrub Top	CoolTech	0.41	lbs	Measured
Scrub Bottom	CoolTech	0.38	lbs	Measured
Laundry bag	Nylon, PVC	1.47	lbs	Measured

The lifecycle of the reusable garment set begins with the manufacturing of each component. They are then transported to UniTech's distribution facility in Morris, IL. From there, each garment set is trucked to the customer. It is assumed that each set is worn only one time between launderings. Once a person exits the contaminated zone they must remove their suit. To re-enter, a clean, uncontaminated suit must be used. After use, the garment set is placed in the provided laundry bag and trucked to the closest UniTech laundering facility. All items, including the laundry bag, are then washed, dried, and tested for persisting radiological contamination. If the remaining amount is allowable, the garment is sent back out for use. If unacceptable levels of contamination are found, the garment is either re-washed or landfilled in an appropriate facility.

3.2.1.1 Manufacturing

Manufacturing data was primarily obtained from existing literature. ProTech, CoolTech, and Nylon are all woven fabrics utilizing a variety of materials. The specifications for ProTech list the fabric components as 99% nylon and 1% carbon fiber, while CoolTech specifications list 99% PET and 1% carbon fiber as the primary materials. The carbon fiber used, however, is a bicomponent nylon 6 yarn, which is at least 90% nylon by mass. Carbon fiber is therefore a small contribution to the total garment mass, accounting for less than 0.1% by mass. As can be seen in Table 3-6 and Table 3-5, the ProTech and CoolTech garments were therefore modeled as 100% Nylon 6 and PET, respectively. The nylon used for the shoe covers and the laundry bag is also 100% Nylon 6, see Table 3-8. The manufacturing process energy and material waste is estimated from a gate-to-gate LCI for woven fabric published by CottonInc.[2] Manufacturing of cotton fiber may be an overestimation of energy used for nylon, but lacking better proxy information, the Cotton Inc. LCI is used as a suitable estimate. Rubber manufacturing data was obtained from the GaBi 6 database, see Table 3-7.

[2] *The Life Cycle Inventory and Life Cycle Assessment of Cotton Fiber & Fabric.* http://cottontoday.cottoninc.com/sustainability-about/LCI-LCA-Cotton-Fiber-Fabric/

Table 3-5: ProTech Manufacturing data

Type	Flow	Amount	Unit	Source	Distance	Unit	Mode
Input	Nylon 6 Yarn	1.09	lbs	Literature	Excluded		
	Electricity	4.00	kWh	Literature	n/a		
	Thermal Energy	0.02	therms	Literature	n/a		
Output	Garment	1.00	lbs	Literature	7,201 2,100 50	mi	Container ship Cargo rail Class 5 truck
	Material Waste	0.09	lbs	Literature			

Table 3-6: CoolTech Manufacturing data

Type	Flow	Amount	Unit	Source	Distance	Unit	Mode
Input	PET Fibers	1.09	lbs	Literature	Excluded		
	Electricity	4.00	kWh	Literature	n/a		
	Thermal Energy	0.02	therms	Literature	n/a		
Output	Garment	1.00	lbs	Literature	7,201 2,100 50	mi	Container ship Cargo rail Class 5 truck
	Material Waste	0.09	lbs	Literature			

Table 3-7: Rubber manufacturing data

Type	Flow	Amount	Unit	Source	Distance		Unit	Mode
Input	Styrene-butadiene rubber	1.41	lbs	Measured	Excluded			
	Electricity	0.58	kWh	Measured	n/a			
	Lubricating oil	0.0142	lbs	Measured	Excluded			
	Water	0.63	gal	Measured	n/a			
Output	Garment	1.00	lbs	Measured	Gloves 6,214 2,230 50	Shoes 5,853 2,230 50	mi	Container ship Cargo rail Class 5 truck
	Material Waste	0.41	lbs	Measured	Excl.			

Table 3-8: Nylon manufacturing data

Type	Flow	Amount	Unit	Source	Distance	Unit	Mode
Input	Nylon 6 Yarn	1.09	lbs	Literature	Excluded		
	Electricity	4.00	kWh	Literature	n/a		
	Thermal Energy	0.02	therms	Literature	n/a		
Output	Garment	1.00	lbs	Literature	7,201 2,100 50	mi	Container ship Cargo rail Class 5 truck
	Material Waste	0.09	lbs	Literature			

3.2.1.2 Transport

Modes of transport and associated distances are primary data obtained from UniTech and are presented in the associated unit process tables.

3.2.1.3 Laundering

Primary data from UniTech facilities was used to calculate the laundering requirements per pound of material processed, including both washing and drying activities, see Table 3-9**Error! Reference source not found.**. This information represents an annual average of all facility usage. Though different materials have different washing and drying requirements, data availability required average values be used for all material being processed. The composition of the laundry chemicals (builder, sour, detergent, and pulse shield) are based on a multitude of MSDSs for chemicals used by UniTech facilities. As the specific chemicals used vary among the different locations, average values for their ingredients were used. Further information is available upon request.

The waste water leaving the facility is filtered before reaching the municipal sewage system, with the exception of one UniTech facility which treats its waste water on site before releasing it to the local watershed. All BOD, COD, and radioactive particles are monitored and maintained to be below the maximum allowed by regulation. The impacts related to treating the water are accounted for in both the facility operation requirements and the application of the GaBi waste water treatment dataset, which assumes average emissions.

Table 3-9: UniTech laundering requirements

Type	Flow	Amount	Unit	Source	Distance	Unit	Mode
Input	Garment	1.00	lbs	Calculated	320	mi	Class 5 truck
	Electricity	0.51	kWh	Calculated	n/a		
	Natural Gas	0.05	therms	Calculated	n/a		
	Water	4.56	gal	Calculated	n/a		
	Builder	0.56	oz	Calculated	Excluded		
	Sour	0.19	oz	Calculated	Excluded		
	Detergent	0.25	oz	Calculated	Excluded		
	Pulse Shield	0.13	oz	Calculated	Excluded		
Output	Garment	1.00	lbs	Calculated	320	mi	Class 5 truck
	Wastewater	3.64	gal	Calculated	n/a		

3.2.1.4 End-of-Life

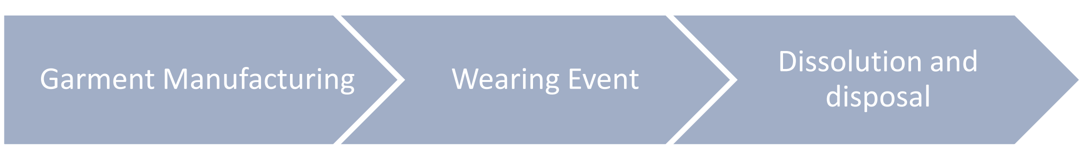
Low-level radioactive waste in the US is generally landfilled in sealed containers, a process also followed by UniTech. The dataset used as a proxy is one for inert material and as such there is no energy credit from landfill gas. The waste is transported an average of 1,150 miles by truck.

3.3 Disposable Protective Garment Set

3.3.1 Overview of Life Cycle

The lifecycle of the disposable garment set, as seen in Figure 3-2, consists of initial garment manufacturing, the wearing event, dissolution of the PVA material, and final incineration of any un-dissolved components. Transportation between stages is also included.

Figure 3-2: Life cycle of disposable garment set



The disposable garment set under consideration in this study is a hot-water soluble, PVA-based material used for all fabric applications, i.e., coverall, hood, shoe covers, and scrub set. The shoes and gloves, however, are both made of rubber. The laundry bag is also made of hot-water soluble PVA, though instead of a non-woven fabric it is a clear film. The above specifications are based on information about disposable garments obtained from a recent LCA study by Eden Nuclear and Environment [Eden 2012]. Table 3-10 lists the materials and weights associated with each component of the disposable garment set.

Table 3-10: Disposable garment set materials and weights

Type	Material	Weight	Unit	DQI
Coverall	PVA fabric	0.67	lbs	Measured
Hood	PVA fabric	0.07	lbs	Measured
Shoe covers	PVA fabric	0.13	lbs	Calculated
Shoes	Rubber	0.29	lbs	Measured
Gloves	Rubber	0.15	lbs	Measured
Scrub Top	PVA fabric	0.24	lbs	Measured
Scrub Bottom	PVA fabric	0.23	lbs	Measured
Laundry Bag	PVA film	0.25	lbs	Measured

3.3.1.1 Manufacturing

There are multiple ways to produce a hot-water soluble PVA garment. While the exact specification for individual garments is proprietary information, it was assumed to be made of partially-hydrolyzed PVA based on existing patents for similar technology [Yang et al. 1997]. Based on the available literature, the garment is made from non-woven fabric, manufactured using a hydroentanglement process. Due to the availability of information, energy requirements for a generic spun bonded process were acquired from literature[3] and used as a proxy for hydroentanglement, see Table 3-11.

Table 3-11: PVA material manufacturing requirements

Type	Flow	Amount	Unit	Source	Distance	Unit	Mode
Input	PVA (88% hydrolyzed)	1.01	lbs	Literature	Excluded		
	Electricity	0.47	kWh	Literature	n/a		
	Natural Gas	1,801	Btu	Literature	n/a		
Output	PVA Material	1.00	lbs	Literature	12,250 330	mi	Container ship Class 5 truck
	Material Waste	0.01	lbs	Literature	Excluded		

3.3.1.2 Transport

Transportation modes and distances for the disposable garment set were obtained from a recent LCA study by Eden Nuclear and Environment [Eden 2012], a comparative study on OREX and textile protective garments used in the USA.

3.3.1.3 End-of-Life

The dissolution process dissolves the PVA garment using hot water and catalyst chemicals, such as hydrogen peroxide. The energy, water, and chemical requirements were obtained from the existing LCA

[3] *Spunbonding process.* http://www.reicofil.com/en/vliesanlagen/p0035_prozess.asp

on disposable garments, as was the remaining waste after dissolution [Eden 2012]. See Table 3-12 for details on the unit process.

Table 3-12: Dissolution process for PVA material

Type	Flow	Magnitude	Unit	Source	Distance	Unit	Mode
Input	Garment	1.00	lbs	Literature	835	mi	Class 5 truck
	Natural Gas	4,550	Btu	Literature	n/a		
	Water	5.28	gal	Literature	n/a		
	H_2O_2	0.37	lbs	Literature	Excl.		
	$FeSO_4$	0.002	lbs	Literature	Excl.		
Output	Waste to incineration	0.06	lbs	Literature	450	mi	Class 5 truck
	Wastewater	5.53	gal	Literature	n/a		
	Carbon Dioxide (emission to air)	0.19	lbs	Calculated	n/a		

Carbon dioxide emissions are released when the PVA reacts in the presence of hydrogen peroxide (H_2O_2) and the catalyst iron sulfate ($FeSO_4$). This is referred to as a Fenton reaction. It creates hydroxyl radicals which help break down pollutants and contaminants. The reaction that occurs ultimately breaks down the PVA fabric into carbon dioxide and water. The amount released will depend on the degree of hydrolysis of the PVA; if the PVA is hydrolyzed at 88% then the remaining 12% is vinyl acetate (VAM), see equations (1) and (2) [Oji 1999, Eastern Technologies 2010].

$$\textbf{(PVA)}\ \mathrm{C_2H_4O + 5H_2O_2 \xrightarrow{\Delta\ FeSO_4} 2CO_2 + 7H_2O} \qquad (1)$$

$$\textbf{(VAM)}\ \mathrm{C_4H_6O_2 + 9H_2O_2 \xrightarrow{\Delta\ FeSO_4} 4CO_2 + 12H_2O} \qquad (2)$$

The amount of hydrogen peroxide used was calculated from the Eden report, which stated that 100-150 kg of "laundry chemicals" was used per 600 lb load [Eden 2012]. The hydrogen peroxide is assumed to be at 100% concentration while the iron sulphate was assumed to be 0.5% by mass of the hydrogen peroxide. The calculated amount of hydrogen peroxide used is not nearly enough to completely break down all the PVA, therefore the PVA is only partially broken down, resulting in shorter carbon chains that can be dissolved in water as opposed to the carbon dioxide and water that would have been generated had the reaction gone to completion. Therefore, the water used for treatment still contains PVA when it is sent to the municipal wastewater treatment, where it ultimately is transformed into sludge. Based on US averages, 60% of this sludge is used as fertilizer, 22% is incinerated, and the remainder goes to no-value land applications. The portion of the remaining PVA that goes to incineration releases its carbon in the form of carbon dioxide. The carbon in the remaining sludge does not get released as carbon dioxide but remains in the land via fertilizer and no-value land use. Therefore, based on the calculations of the above stoichiometric equations and the amount of hydrogen peroxide assumed to be used, just 0.19 kg of CO_2 is released per kg of PVA fabric treated. Additionally, due to the incineration of the resulting sludge at EoL, 0.28 kg of CO_2 is released per kg of PVA fabric.

3.4 Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory 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 3-13 and Table 3-14 only display 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.

The complete inventory is available upon request from the study authors.

Table 3-13: LCI results of Reusable garment set (kg/Use)

Type	Flow	Materials	Transportation	Laundering	End-of-Life	Total
Resources	**Crude oil**	6.44E-01	3.56E-01	1.74E+00	1.46E-02	**2.76E+00**
	Hard coal	2.19E-01	1.03E-01	5.35E-01	4.26E-03	**8.61E-01**
	Lignite	2.19E-01	1.03E-01	5.35E-01	4.26E-03	**8.61E-01**
	Natural gas	2.19E-01	1.03E-01	5.35E-01	4.26E-03	**8.61E-01**
Emissions to air	**CO_2**	5.31E-07	5.15E-08	7.90E-06	1.46E-09	**8.48E-06**
	CO	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
	NO_2	4.26E-01	2.52E-01	1.21E+00	1.04E-02	**1.90E+00**
	NO	4.26E-01	2.52E-01	1.21E+00	1.04E-02	**1.90E+00**
	SF_6	4.25E-01	2.52E-01	1.21E+00	1.04E-02	**1.89E+00**
Emissions to water	**NH_3**	2.09E-13	1.20E-14	1.76E-12	3.56E-16	**1.99E-12**
	NO_3^-	2.77E-05	5.76E-06	1.27E-04	2.38E-07	**1.60E-04**
	PO_4^{3-}	3.64E-05	2.30E-05	6.36E-04	9.70E-07	**6.97E-04**

Table 3-14: LCI Results of disposable garment set (kg/Use)

Type	Flow	Materials	Transportation	Laundering	End-of-Life	Total
Resources	**Crude oil**	4.06E+00	2.40E-01	0.00E+00	3.40E-01	**4.64E+00**
	Hard coal	8.31E-01	2.16E-01	0.00E+00	2.17E-02	**1.07E+00**
	Lignite	6.82E-01	7.16E-03	0.00E+00	7.33E-02	**7.62E-01**

Type	Flow	Materials	Transportation	Laundering	End-of-Life	Total
	Natural gas	9.53E-02	1.04E-03	0.00E+00	2.12E-02	**1.18E-01**
Emissions to air	CO_2	7.83E+00	6.19E-01	0.00E+00	1.17E+00	**9.62E+00**
	CO	7.82E+00	6.18E-01	0.00E+00	1.17E+00	**9.61E+00**
	NO_2	5.90E-03	1.73E-03	0.00E+00	4.93E-04	**8.12E-03**
	NO	1.69E-06	4.38E-09	0.00E+00	6.71E-07	**2.36E-06**
	SF_6	5.89E-06	4.31E-08	0.00E+00	5.02E-06	**1.10E-05**
Emissions to water	NH_3	3.03E-04	3.86E-05	0.00E+00	2.47E-04	**5.89E-04**
	NO_3^-	4.39E-06	7.48E-08	0.00E+00	9.17E-07	**5.38E-06**
	PO_4^{3-}	2.85E-04	3.85E-05	0.00E+00	2.22E-04	**5.45E-04**

4 Life Cycle Impact Assessment (LCIA)

This chapter presents the potential environmental impacts associated with a single wearing event of either a reusable or disposable protective garment set. Abbreviations for the impacts have been described in Table 2-3 and Table 2-4, and are reproduced here for reference.

- Environmental Impact Categories:
    - Global Warming Potential (GWP) [kg CO_2 eq];
    - Acidification Potential (AP) [kg SO_2 eq];
    - Eutrophication Potential (EP) [kg N eq];
    - Smog Formation Potential (SFP) [kg O_3 eq];
    - Ozone Depletion Potential (ODP) [kg CFC 11 eq];
- Environmental Indicators:
    - Primary Energy Demand, Non-renewable (PED) [MJ];
    - Water Consumption (Water) [kg Water]

The results are broken down into four life cycle stages:

1. **Materials:** includes energy and materials associated with the manufacturing of all components of the protective garments
2. **Transportation:** includes initial transport associated with materials, transport to and from the customer, and transportation to end-of-life processing and/or disposal
3. **Laundering:** includes energy and materials associated with washing and drying the reusable garment set
4. **End-of-Life:** includes any energy and materials required for processing and disposal of the protective garments, including any process emissions

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 emitted molecules 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 Impact Assessment Results

This section presents the potential environmental impacts for one use of each protective garment. Figure 4-1 shows the relative contributions of each life cycle stage for the reusable garment set. It can be seen that both material manufacturing and laundering contribute significantly to the total, while transportation has a much smaller impact and EoL treatment is negligible.

Figure 4-2 shows the same results but for the disposable garment set. In this case, the impacts are overwhelmingly due to the manufacturing of the garment. Additionally, both transportation and EoL processing, combined, contribute anywhere from 10-30% of lifetime impacts. The CO_2 emissions from the chemical reaction that occurs during dissolution of the disposable garment set only contribute approximately 1% of the lifetime impact.

Note that all results in this chapter are based on the reusable garment set assuming different number of uses for each garment as shown in Table 3-4: Reusable garment set materials and weights (size: large)Table 2-1 (e.g., the coverall is used 48 times).

Figure 4-1: Lifetime environmental impacts of the reusable garment set as a percent of total

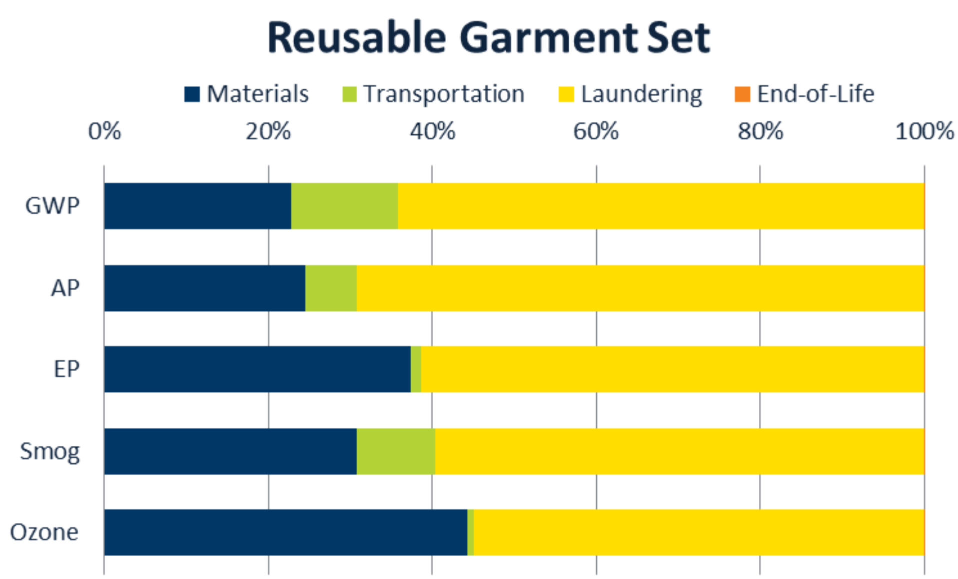
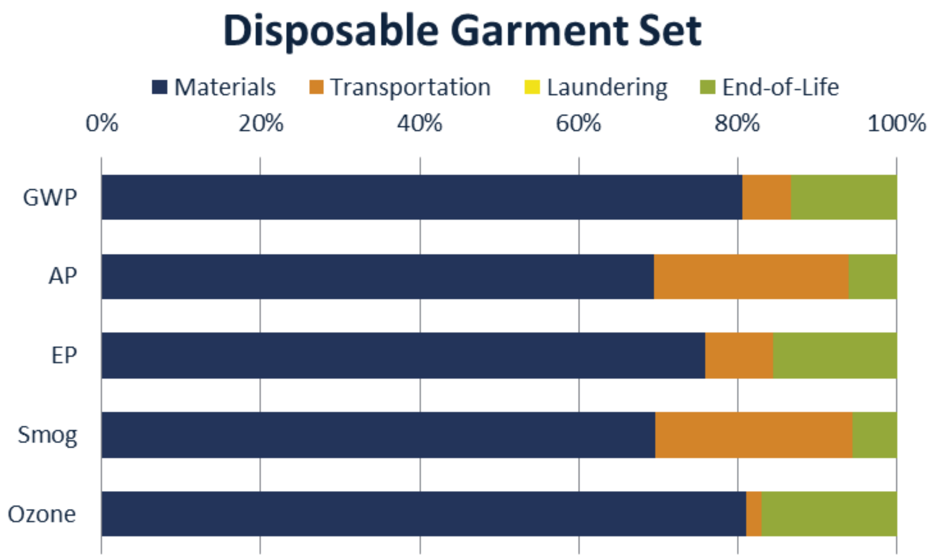


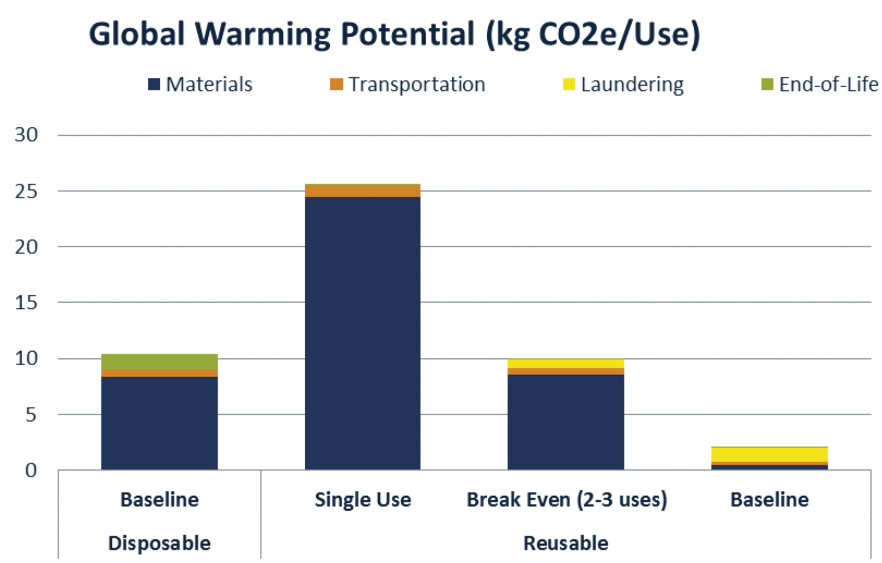
Figure 4-2: Lifetime environmental impacts of the disposable garment set as a percent of total



4.1.1 Global Warming

The results presented in Figure 4-3 show that for a single wearing event, the reusable garment set has only 19% the GWP of the disposable set alternative. This is overwhelmingly due to the manufacturing burden of the disposable set option. The EoL processing required for the disposable garment set is also significant when compared to the marginal impacts at EoL of the reusable garment set. This is due to the heating energy and chemicals required. A break-even scenario is also shown, which represents the unlikely scenario that the reusable garment set is only used 2 – 3 times.

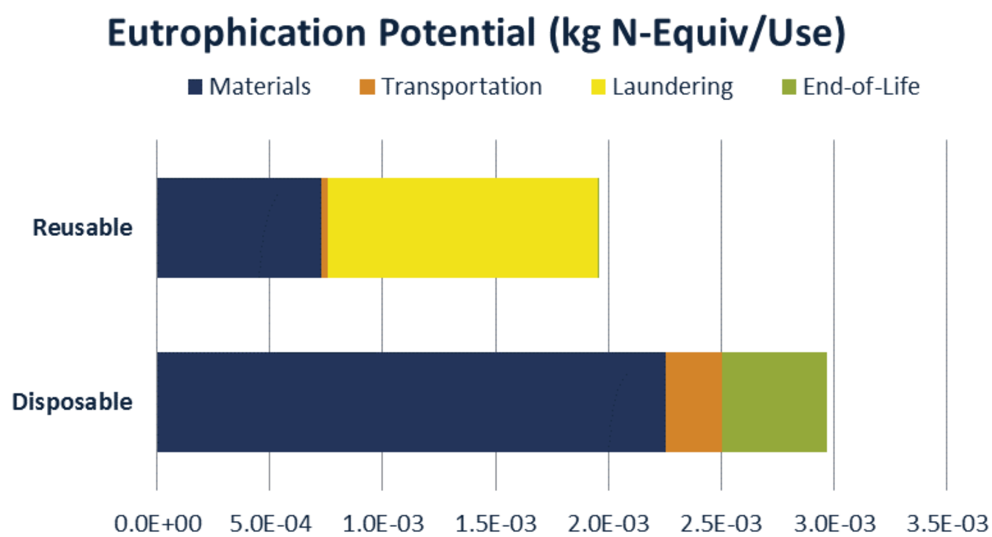
Figure 4-3: GWP per use, full life-cycle results



4.1.2 Eutrophication

The difference between reusable and disposable garment sets is much less significant when considering the Eutrophication Potential, see Figure 4-4. The impact of the reusable set is 81% that of the disposable set. Much of this is due to the increased wastewater treatment required during laundering, which releases macronutrients to the environment.

Figure 4-4: Eutrophication Potential per use, full life-cycle results



4.1.3 Acidification and Smog

Figure 4-5 and Figure 4-6 present the results for acidification and smog formation, respectively. Both show the use of the reusable garment set having a smaller impact than the use of the disposable set alternative. Compared to the disposable set, the reusable set has 27% of the acidification impacts and 17% of the smog formation potential.

Figure 4-5: Acidification Potential per use, full life-cycle results

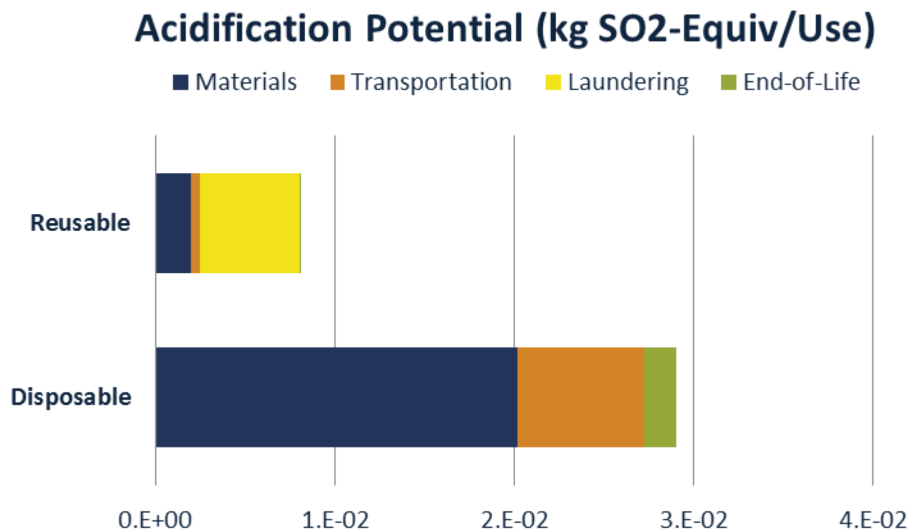
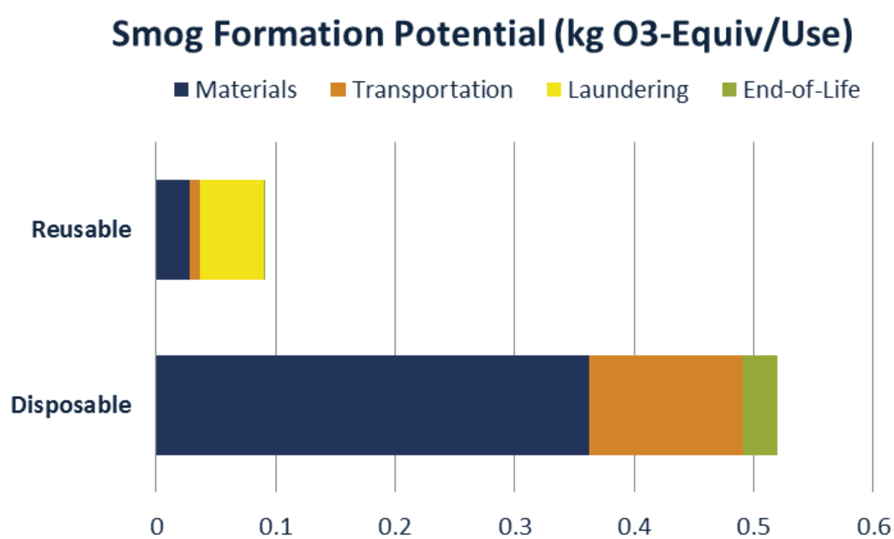


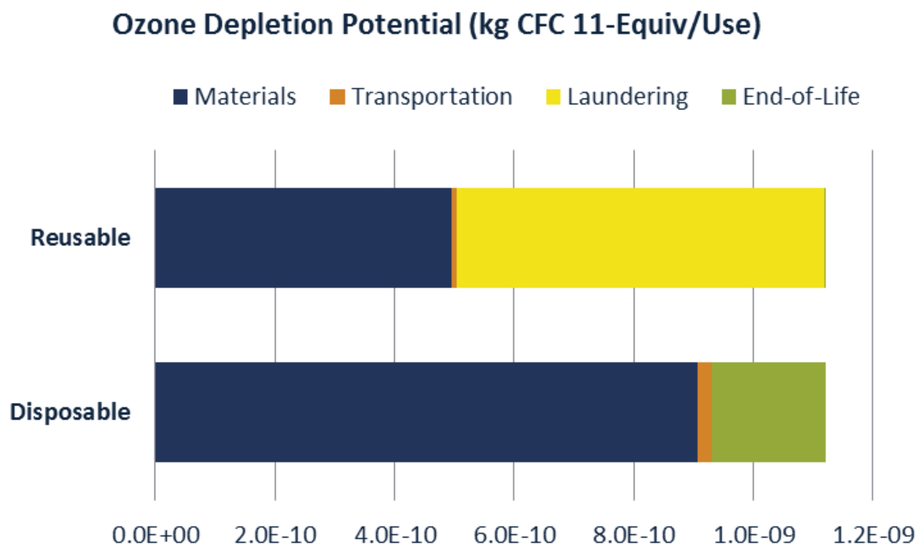
Figure 4-6: Smog Formation Potential per use, full life-cycle results



4.1.4 Ozone Depletion

Finally, the ozone depletion potential comparison presented in Figure 4-7 shows a much closer result, with the reusable and the disposable garment sets rendering virtually the same result.

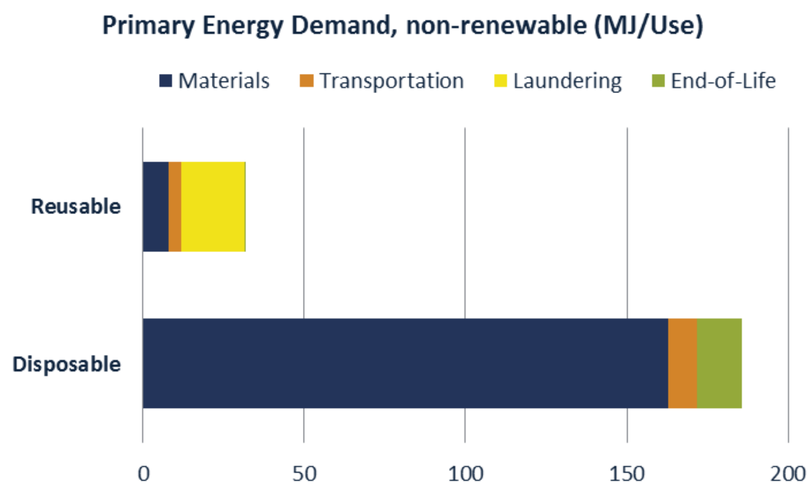
Figure 4-7: Ozone Depletion Potential per use, full life-cycle results



4.2 Inventory Indicators

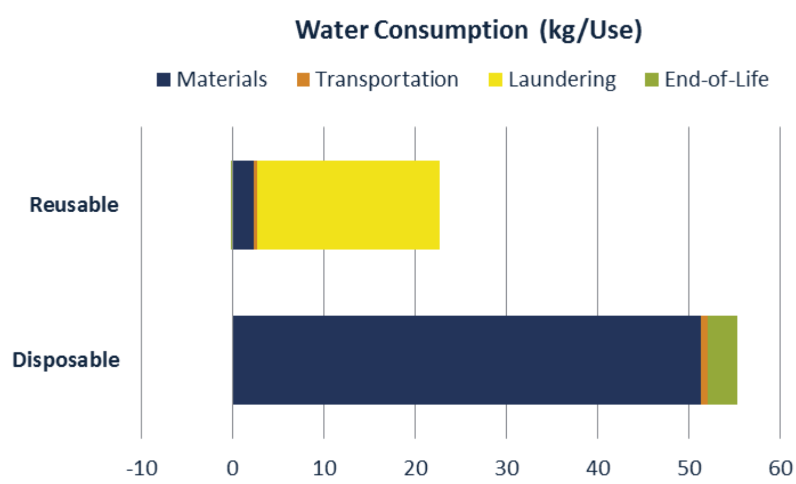
This section presents the results of the selected inventory indicators, Primary Energy Demand and Water consumption. Figure 4-8 shows that the use of the reusable garment set requires 17% of the non-renewable energy resources than the disposable garment set requires.

Figure 4-8: Primary Energy Demand per Use, full life-cycle results



Similarly, Figure 4-9 shoes that reusable garment set results in less water consumption than the disposable set. The reusable set requires 60% less water than that required by the disposable set. This is due to the water requirements of manufacturing PVA.

Figure 4-9: Water Consumption per use, full life-cycle results



5 INTERPRETATION

5.1 Identification of Relevant Findings

In summary, the study determined that the reusable protective garment set has roughly five-fold less impact than the disposable protective garment set for global warming potential, smog, and primary energy demand. The reusable garment set has three-fold less impact than the disposable set for acidification potential and water use, while eutrophication potential is about three-fourths the impact.

Within the disposable garment set the materials and manufacturing had the largest impact, while the reusable garment set impacts were most significantly associated with the required laundering.

Previous studies have been conducted comparing reusable and disposable protective garment options. One, which focused on the OREX® disposable product specifically, was conducted by Eden Nuclear and Environment and SKM Enviros in 2012. The Eden study was referenced multiple times by the present study for background information on the disposable garment set. However, the final conclusions made by this study and the Eden study are completely different.

The Eden study states that "the carbon footprint of a single use OREX garment offers better environmental performance compared to a nylon one up to 80 to 90 uses" [20]. This incorrect conclusion is directly related to the inappropriate use of proxy data in the Eden study. Instead of using the environmental impacts of polyvinyl alcohol manufacturing, the Eden study uses the emissions factor for polyvinyl acetate, a precursor to PVA. A hydrolysis step is required to convert polyvinyl acetate into polyvinyl alcohol. The hydrolysis step adds a significant amount of environmental burden, e.g., for GWP hydrolysis is responsible for an increase from 1.99 kg CO_2eq. / kg of polyvinyl acetate to 8.78 kg CO_2eq. / kg of PVA, with is greater than a fourfold error.

Since the raw materials, and specifically the polyvinyl alcohol, make up anywhere from 65% to 85% of the environmental burden of the disposable garment set, the correct or incorrect choice of PVA dataset is significant enough to dramatically change the final conclusions.

5.2 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 on a study serving as a data source) 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 LCI database were used. The LCI data sets from the GaBi LCI 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.

5.2.1 Precision and completeness

- ✓ **Precision:** As the relevant foreground data is modeled based on primary information sources of the owner of the reusable garment set laundering technology, no better precision is reachable.

Seasonal variations were balanced out by using yearly averages. The disposable garment set technology was modeled using conservative lower values from literature. Primary data would increase the precision of the comparison, but would not change the conclusion. All background data is GaBi data with the documented precision**.**

- ✓ **Completeness:** Each unit process was checked for mass balance and completeness of the emission inventory. No data was knowingly omitted.

5.2.2 Consistency and reproducibility

- ✓ **Consistency:** To ensure consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases. The system boundary, allocation method, and impact assessment methods, along with other methodological choices, were made consistently throughout the model.

- ✓ **Reproducibility:** Reproducibility, though not a goal of this study is possible to a certain extent through the disclosure of input-output data, dataset choices, and modeling approaches in this report.

5.2.3 Representativeness

- ✓ **Temporal:** All primary data were collected for the year September 2011 through August 2012. All secondary data comes from the GaBi 6 2012 databases and are representative of the year 2011, and are valid until the year 2014. As the study intended to compare the product systems for the reference year September 2011-August 2012, temporal representativeness is considered to be high.

- ✓ **Geographical:** All primary and secondary data were collected specific to the countries / regions under study. Where country / region specific data were unavailable, proxy data were used (see Section 2.8). 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 (see Chapter 2.8). Technological representativeness is considered to be high.

5.3 Sensitivity

The following sensitivity analyses were performed to test the robustness of the results towards uncertainty and main assumptions. Detailed results can be found in Appendix B.

5.3.1 Lifetime Uses

A key parameter in this comparison is the lifetime uses of each component of the reusable garment set. As the number of uses increase, the allocated impact per use decreases. While UniTech records average lifetime washes of their garments using RFID tags among other things, the values for the number of uses one can get out of a garment are a potential source of debate. Therefore, a scenario analysis is used to test the robustness of the conclusions made in this study.

Figure 5-1 shows the baseline GWP for the disposable and reusable garment sets, along with three other scenarios for possible lifetime uses of the reusable garment set. Table 5-1 lists the lifetime uses of each component of the reusable garment set, for each scenario. The 'single use' scenario depicts the lifetime impacts if a reusable garment set were used like the disposable set – worn once, then disposed of. The 'break even' scenario shows the minimum number of uses of the reusable garment set needed to result in a similar GWP as the disposable set. This is between two and three depending on the garment.

Figure 5-1: GWP, Lifetime use of reusable garment set sensitivity results

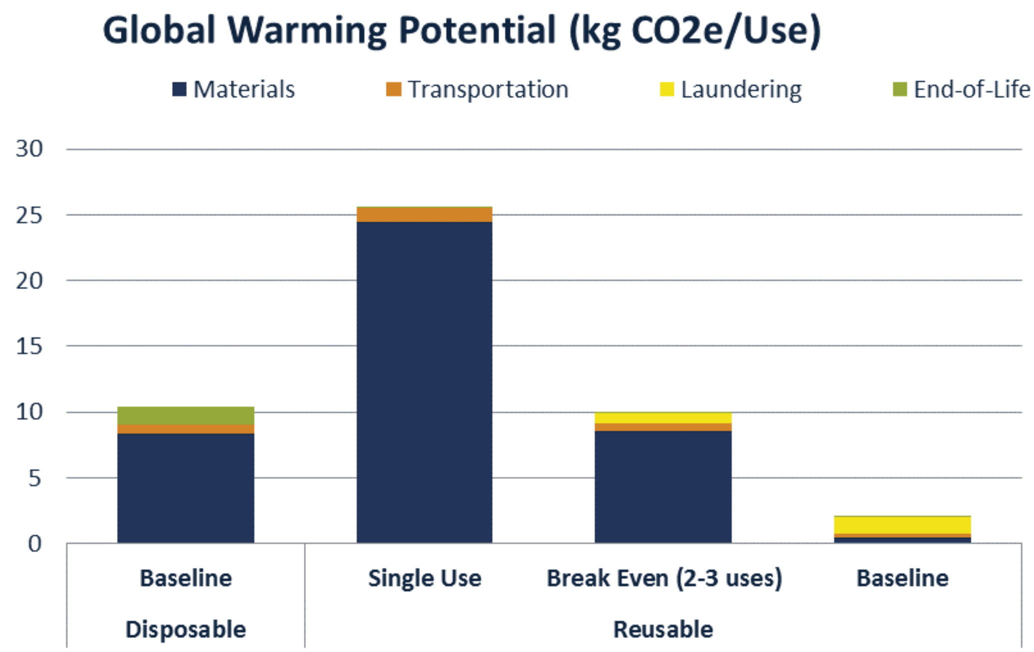


Table 5-1: Lifetime use scenarios

Type	Single Use	Break Even	Baseline
Coverall	1	3	48
Gloves	1	2	9
Hood	1	3	200
Shoes	1	2	23
Shoe covers	1	3	88
Scrub Top	1	3	200
Scrub Bottom	1	3	200
Laundry bag	1	3	140

The total number of wash cycles over a garment's lifetime is one less than the number of uses since the garment need not be washed before the first use or after the final use. As such, when allocating for a single use, the contribution from laundering is scaled by the number of washes divided by the number of uses, not washes. As the number of lifetime uses increases, this scaling factor approaches 1. Therefore, the contribution of laundering to the total impact per use of the reusable garment set increases with lifetime uses, up to a point.

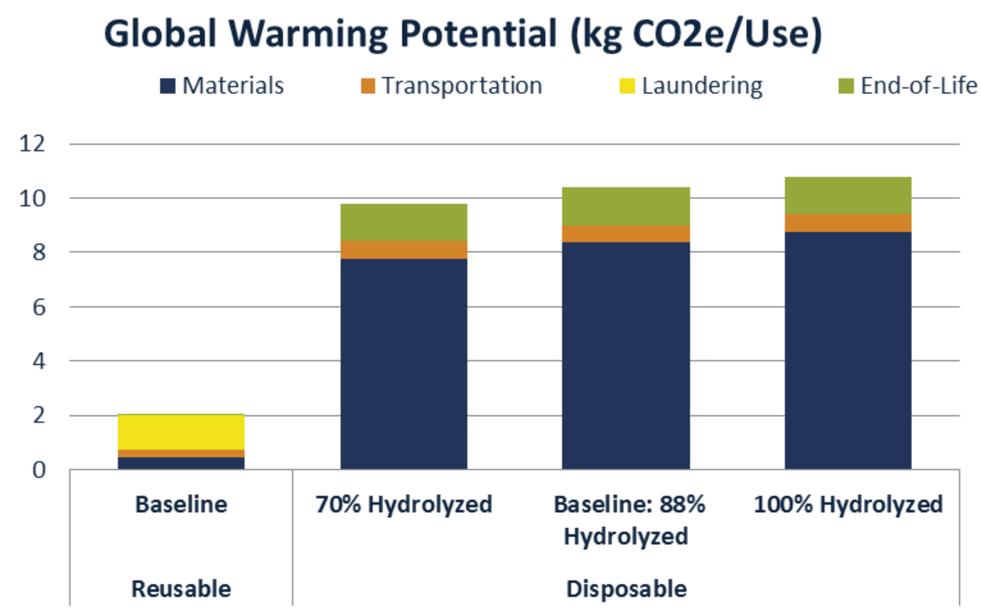
This scenario analysis shows that to have a lower impact than the disposable set alternative, a reusable garment set needs to be worn at least 2-3 times, which is far below actual usage behavior. This confirms the original conclusion of the study, that the reusable personal protection equipment (PPE) set has reduced environmental impacts compared to disposable protection equipment set.

5.3.2 PVA Hydrolysis

Initial results showed that the largest contributor to the environmental impacts associated with the disposable garment set were due to the material manufacturing, which warranted further research on PVA-based fabrics.

Existing literature shows that the degree of hydrolysis required can vary significantly. A search through U.S. patents yielded degrees of hydrolysis at 88% (Yang et al. 1997), 70-95% (Langley 1999), and 98% (Honeycutt 1999). Figure 5-2 shows how the total GWP of the disposable garment set varies with degree of hydrolysis. While the value chosen does affect the total, it does not change the conclusion of this study, as the reusable garment set still has a significantly lower impact.

Figure 5-2: Degree of Hydrolysis scenario analysis results, GWP



The degree of hydrolysis also affects the amount of process emissions released during dissolution. However, since the amount of chemicals used did not allow for the all the PVA to react, the effect is lessened. At 70% hydrolysis 0.196 kg CO_2e is released per kg of PVA, while at 100%, 0.190 kg CO_2e is released. Should all the PVA react, this impact would be much more significant. Given further information on the processing requirements of the material, the impact of hydrolysis on the EoL dissolution emissions could be revisited to increase the precision of the comparison.

5.4 Conclusions, Limitations, and Recommendations

5.4.1 Conclusions

In conclusion, the reusable protective garment set clearly has substantially lower environmental burdens compared to a disposable set alternative. This holds true across all the impact categories and inventory indicators assessed by this study. The lifetime uses of the reusable garment set has a significant effect on the associated impacts per use, but a relatively low (and easily surpassed) number of uses is required to validate this conclusion. The degree of hydrolysis in PVA manufacturing does alter the impact due to materials for the disposable garment set, but is not a significant contributor to lifetime environmental impacts. It was found to not alter the conclusion of the study.

5.4.2 Limitations & Assumptions

This study assumed the disposable garment set was made entirely of PVA. There are various ways to make water-soluble PVA garments, however, and the precise mix of materials used by OREX® is unknown. This could affect the final impact of the disposable garment set, potentially reducing the impact associated with the material manufacturing. This would most likely not change the conclusion of the study but would affect the precision of the individual results. Additionally, little information was available on the dissolution process utilized for the disposable garment set under study. Throughout the study conservative, lower values were used, so more information would most likely not change the results, but would increase their accuracy.

A limitation of this study was the lack of available data on the cut and sew processes required to manufacture the different components of the garment sets. While initial impacts would most likely be similar between the two sets, impacts per use would be much smaller for the reusable garment set, as they would be distributed over the possible lifetime uses of the garment. This supports the original conclusion of this study.

5.4.3 Recommendations

While, in this case, a reusable protective garment set is better than a disposable garment set for the environment, improvements can still be made in reducing the environmental impacts of a reusable garment set. Washing energy and water use were found to be significant contributors to lifetime impacts. Initiatives focused on reducing the impacts of the washing facilities can significantly reduce the environmental burdens attributed to a reusable garment set. Transportation is a small contributor, so only limited effort should be spent on improving route efficiency or truck utilization.

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7 Appendix A – Impact Assessment Results

Table 7-1: Detailed LCIA Results

	Materials	Transportation	Laundering	End-of-Life	Total
Global Warming Potential (kg CO_2-Equiv/Use)					
Reusable	4.54E-01	2.61E-01	1.28E+00	1.62E-03	**2.00E+00**
Disposable	8.37E+00	6.40E-01	0.00E+00	1.38E+00	**1.04E+01**
Acidification Potential (kg SO_2-Equiv/Use)					
Reusable	1.97E-03	5.08E-04	5.57E-03	6.73E-06	**8.05E-03**
Disposable	2.02E-02	7.09E-03	0.00E+00	1.76E-03	**2.91E-02**
Eutrophication Potential (kg N-Equiv/Use)					
Reusable	7.29E-04	2.65E-05	1.20E-03	1.03E-06	**1.95E-03**
Disposable	2.26E-03	2.50E-04	0.00E+00	4.64E-04	**2.97E-03**
Smog Formation Potential (kg O_3-Equiv/Use)					
Reusable	2.77E-02	8.60E-03	5.35E-02	1.05E-04	**8.99E-02**
Disposable	3.62E-01	1.29E-01	0.00E+00	2.87E-02	**5.20E-01**
Ozone Depletion Potential (kg CFC 11-Equiv/Use)					
Reusable	4.95E-10	8.62E-12	6.16E-10	1.99E-13	**1.12E-09**
Disposable	9.07E-10	2.29E-11	0.00E+00	1.90E-10	**1.12E-09**

Table 7-2: Detailed Inventory Indicator Results

	Materials	Transportation	Laundering	End-of-Life	Total
Primary Energy Demand, Non-renewable (MJ/Use)					
Reusable	8.04E+00	3.82E+00	1.97E+01	2.56E-02	**3.16E+01**
Disposable	1.63E+02	8.91E+00	0.00E+00	1.38E+01	**1.86E+02**
Water Consumption (kg/Use)					
Reusable	2.28E+00	3.81E-01	2.00E+01	-6.13E-02	**2.26E+01**
Disposable	5.13E+01	7.80E-01	0.00E+00	3.22E+00	**5.53E+01**

8 APPENDIX B – SENSITIVITY ANALYSIS

Table 8-1: Lifetime Use Sensitivity Results (kg CO_2-Equiv/Use)

		Materials	Transportation	Laundering	End-of-Life
Disposable	Baseline	8.37	0.64	0	1.3844
Reusable	Single Use	24.5	1.06	0	0.0655
	Break Even	8.57	0.545	0.825	0.0244
	Baseline	0.454	0.2609	1.28	0.00162

Table 8-2: PVA Degree of Hydrolysis Sensitivity Results (kg CO_2-Equiv/Use)

		Materials	Transportation	Laundering	End-of-Life
Reusable	Baseline	0.454	0.2609	1.28	0.00162
Disposable	70% Hydrolyzed	7.77	0.64	0	1.386
	Baseline: 88% Hydrolyzed	8.37	0.64	0	1.3844
	100% Hydrolyzed	8.76	0.64	0	1.3841