Life Cycle Inventory Comparison of Radiological Protective Garments

Summary

UniTech Services Group, Inc. (UniTech) commissioned Exponent to study the environmental consequences of using launderable protective clothing as compared with using single-use polyvinyl alcohol (PVA) clothing. Both garment types are currently used in the United States (U.S.) nuclear industry as protective wear for individuals. As part of the life cycle inventory (LCI) evaluation, Exponent estimated water use, energy use, and greenhouse gas emissions for fabric production and garment manufacture, and for use, laundering and disposal of both PVA garments and reusable nylon garments. The lifetime of the reusable garment was assumed to be 100 wearings based on historical garment wear information from UniTech, while the lifetime of the PVA garment was assumed to be 1 wearing.

The bulk of the environmental effects for both garment types occur during fabric production and garment manufacture. More limited effects occur during dissolution of PVA garments and laundering of reusable clothing. Because the manufacturing process predominates in terms of environmental effects, and because manufacturing only occurs once for each garment, reusable garments have less of an overall environmental impact on a per-wear basis than disposable garments. For reusable garments, the environmental effects of manufacturing can be distributed over multiple (approximately 100) wearings. Dissolvable PVA garments must be manufactured once for each wearing, so the entirety of manufacturing-related environmental effects is imposed each time a disposable garment is worn. Based on the assumptions made in this study, one use of a PVA garment releases almost 18 times more greenhouse gas equivalents than one use of a reusable nylon garment.

UniTech estimates that workers in the U.S. nuclear industry wear a combination of 1,700,000 multiple and single use coveralls each year. Therefore, using 100 percent reusable coveralls

instead of 100 percent single-use PVA coveralls would result in a reduction in the overall environmental impact of approximately 28,000 metric tons of greenhouse gas equivalents each year in the U.S. If just one nuclear power plant switched from using single-use PVA to reusable nylon coveralls, the resulting savings would be approximately 475 metric tons per year.

Similar reductions in environmental impact were observed in LCI studies on disposable diapers (nappies), textile products (e.g., napkins, towels), and health-care garments, demonstrating that the environmental footprint of reusable products shrinks as the number of wearings/uses increases relative to their disposable product counterparts.

LCA Perspective

As defined by the United Nations Environment Program (UNEP) Life Cycle Initiative,[1] a life cycle assessment (LCA) is "an analytical tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle." As outlined in ISO 14040:2006[2] and ISO 14044:2006,[3] an LCA is one tool that has been standardized to evaluate the cradle-to-grave consequences of making and using products. The four main phases to an LCA are: goal definition and scoping of issues, inventory analysis, impact assessment, and improvement assessment (See Figure 1). Elements of an LCA involve investigations of extraction and processing of raw materials; manufacturing and product formulation; transportation and distribution; use, reuse, and maintenance; recycling; and final disposal. The focus of an LCA is on quantifying ecological and human health impacts, resource depletion, emissions to air and water, and solid-waste generation.

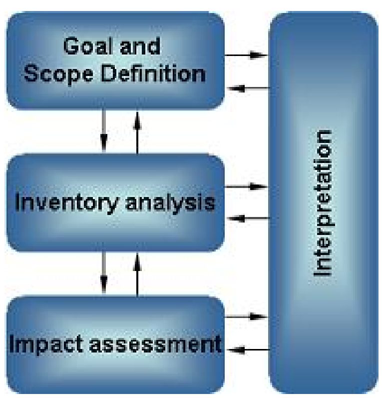

Figure 1. Phases of a life-cycle assessment[4]

During the life-cycle inventory (LCI) phase of the LCA, data on the inputs and outputs during specific aspects of the product life cycle are compiled. The LCI described in this document focuses on fabric production and garment manufacture, and the use, reuse, and disposal of

1 See http://jp1.estis.net/builder/includes/page.asp?site=lcinit&page_id=15CFD910-956F-457D-BD0D-3EF35AB93D60
2 ISO 14040:2006. *Environmental Management—Life Cycle Assessment—Principles and Framework*
3 ISO 14044:2006. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*
4 See http://jp1.estis.net/builder/includes/page.asp?site=lcinit&page_id=15CFD910-956F-457D-BD0D-3EF35AB93D60

radiological protective garments (specifically coveralls) for the nuclear power industry. Variables assessed for the two garment types (PVA single-use, conventional nylon multiple-use) included three parameters: 1) water use, 2) energy use, and 3) greenhouse gas emissions. The study evaluated the three parameters during fabric production and garment manufacture, during the PVA dissolution process, and during laundering of the reusable nylon garments. An assessment of other aspects of the product life cycle—such as raw material acquisition; delivery of new and washed garments, pickup of used garments, and transport of garment loads to the dissolution or laundry facility; operational aspects of laundry and dissolution facilities, (e.g., lighting, HVAC), and management of wastewater and solid-waste disposal—were not included in this evaluation; however, it is reasonable to assume they would be roughly equivalent for the two garment types.

Individual companies, industry trade associations, non-governmental organizations, regulatory agencies, and universities have performed other LCI studies to compare a number of similar products, manufacturing processes, and operational procedures over the past 20 years. Some of the earliest LCI (and complete LCA) studies were done with consumer products such as detergents, diapers (nappies), cups (paper vs. Styrofoam), and bottles (plastic vs. glass). Recent LCI studies have included evaluations of transportation fuels, electrical and electronic products, building and construction materials, batteries, and carpeting, in addition to a variety of consumer products and industrial processes.

LCI Studies of Disposable vs. Reusable Products

Exponent searched the literature to find studies comparing environmental aspects of other multiple use and single use products. Some of the LCI studies focused on comparisons of resource consumption, energy use, and greenhouse gas emissions associated with aspects of manufacturing, use, and/or disposal for single-use (disposable) and multiple-use (reusable) products. Evaluation of disposable vs. reusable diapers (nappies) is probably the most well-known and extensively studied example, with multiple LCI studies conducted in the U.S.,[5]

[5] Franklin Associates Ltd. 1990. Energy and environmental profile analysis of children's disposable and cloth diapers. As discussed in LeVan 1995.

Canada,[6] and Europe[7,8] (see references in these documents for citations of additional diaper LCI studies). Results vary in these studies depending on the assumptions used for variables such as total number of diapers of each type used, number of times cloth diapers were reused (functional unit), washing and drying conditions (e.g., temperature used for washing and drying, energy efficiency of appliances, and use of air drying), and packaging and transport. In some of the studies, and under some of the categories evaluated, reusable diapers had a more beneficial global warming potential, while disposable diapers were more beneficial in other categories. Overall, there were no significant differences among the environmental footprints of disposable diapers, home-laundered reusable diapers, and commercial laundered reusable diapers.[7] For the disposable diapers, the main sources of environmental impact are associated with raw material production and diaper manufacture, while the main sources for the home and commercial laundered reusable diapers are associated with the fuels and electricity consumed by the laundry activities.[8]

Additional LCI studies have been conducted comparing reusable and disposable towels and napkins,[9] as well as other types of fabric products. Results from these studies, as well as LCI studies of cotton, wool, polyester, and nylon textiles[10,11,12,13] and polyester blouses[14] and cotton t-shirts,[15] showed that the majority of energy and water use and greenhouse gas emissions were associated with fabric production and laundering activities. **LCI studies on hospital gowns[9,16,17,18,19] are comparable to this study of radiological garments**. The studies on hospital gowns focused on manufacture and reuse, with no evaluation of capital processes, human labor, or transport of raw materials and finished garments. Fabric production was the largest energy and water consumer for each garment type and produced the most greenhouse gas

6 Vizcarra et al. 1994
7 Aumônier and Collins 2005
8 Aumônier et al. 2008
9 Lehrburger and Mullen 1992
10 Kalliala and Nousiainen 1999
11 Cherrett et al. 2005
12 Barber and Pellow 2006
13 Boustead 2005
14 Franklin Associates 1993
15 Queensland University of Technology 2009
16 Schmidt 2000
17 Ponder and Overcash 2007
18 Zins 2006
19 Ponder 2009

emissions (determined as carbon dioxide (CO_2) equivalents). Based on estimates of total energy and resource consumption, and greenhouse gas emissions associated with their manufacture and laundering, a single reusable hospital gown would consume more energy and natural resources than a disposable gown, but, when washing and reuse were considered, reusable gowns had a smaller overall environmental footprint than disposable gowns over their functional lifetime.[12,14] Comparisons in these studies were made between 1,000 reusable gowns (used 75 times) and 75,000 disposable gowns (functional unit of 75,000 patient gown uses).

Radiological Garment Comparison

UniTech commissioned this study by Exponent to determine and compare the energy and water consumption and greenhouse gas emissions (determined as CO_2) associated with fabric production and garment manufacture of single and multiple-use garment types, laundering and reuse of the conventional nylon multiple-use garments, and dissolution of the PVA single-use radiological protective garments following one wearing.

Fiber and fabric production are the most energy and water-intensive steps in the LCI, and produce the most greenhouse gas emissions, because they require heat and electrical input and resource consumption during the manufacturing process.[20,21,22,23] Since PVA and nylon are both synthetic petrochemical-based materials, the extraction and manufacturing processes for each type of raw material likely require similar amounts of energy and water, and resulting greenhouse gas emissions for each kg of fabric produced. Calculations of water and energy use and carbon dioxide emissions associated with fiber, fabric production and garment manufacture for the two garment types were based on information available in the literature on polyester and nylon fiber and fabric production[23,25,24] and apparel manufacture.[25,26]

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20 Kalliala
21 Cherrett et al. 2005
22 Kalliala and Nousiainen 1999
23 Barber and Pellow 2006
24 Boustead 2005
25 Ponder 2009
26 Franklin Associates 1993

Exponent obtained information on the PVA dissolution process and system configuration from the EPRI and TXU-Comanche Peak (2002) report. As summarized in this document, PVA materials are loaded into a solution tank that is filled with water and heated. Hydrogen peroxide is then added to the tank to oxidize the dissolvable PVA materials into a dilute solution of organic acids and intermediates. After a period of recirculation and cooling, the solution is transferred to a surge tank, where it can be monitored for radioactivity and discharged to a publicly-owned treatment works (POTW), filtered prior to discharge to the POTW, or directed to a bioreactor for additional treatment of the PVA oxidation products before discharge.

Calculations of energy requirements to heat the water, operate the pumps, and conduct the PVA oxidation process through addition of hydrogen peroxide were performed. Carbon dioxide emissions associated with these activities were also calculated. The batch size and water use per batch were determined from the information provided in the EPRI and TXU-Comanche Peak (2002) report. No estimations of the energy requirements, water use, or carbon dioxide emissions associated with wastewater treatment or solid-waste disposal, or with transport of used garments to the dissolution facility, were included in the analysis.

Exponent based its calculations of water and energy use and carbon dioxide emissions associated with laundering of the conventional nylon multiple-use garments for this study on information provided by UniTech. UniTech provided information on total laundry loads, water usage, and energy usage per year, and CO_2 emissions across all eight company facilities and for each facility separately. This study makes no attempt to differentiate usage and emissions calculations among facilities. Rather, total values or estimates were divided by the number of facilities to obtain a single estimate representative of the group.

Assumptions and Calculations

A number of assumptions were made before performing the calculations for each garment type (Table 1). These assumptions are based on information obtained from the previously-discussed studies evaluating polyester and nylon fiber and fabric production and garment manufacture, the EPRI and TXU-Comanche Peak (2002) report, from UniTech, or from equipment operation instructions.

Using the assumptions summarized in Table 1, calculations of energy and water use and CO_2 emissions were performed for each garment type on an individual garment and functional unit[27] basis. As summarized in Figure 2, calculated energy, water use, and CO_2 emissions were slightly greater for a conventional nylon multiple-use garment compared to a PVA single-use garment when compared on an individual garment basis.

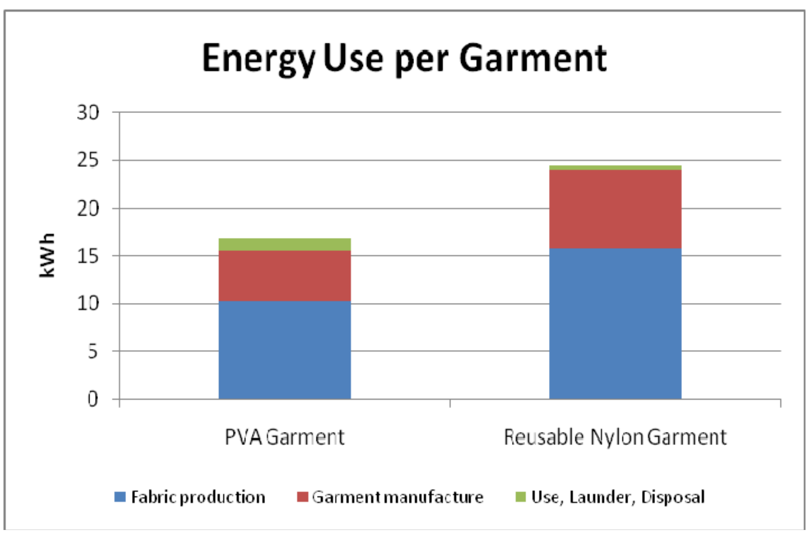
Table 1. Assumptions used in energy and water usage and CO_2 emissions calculations

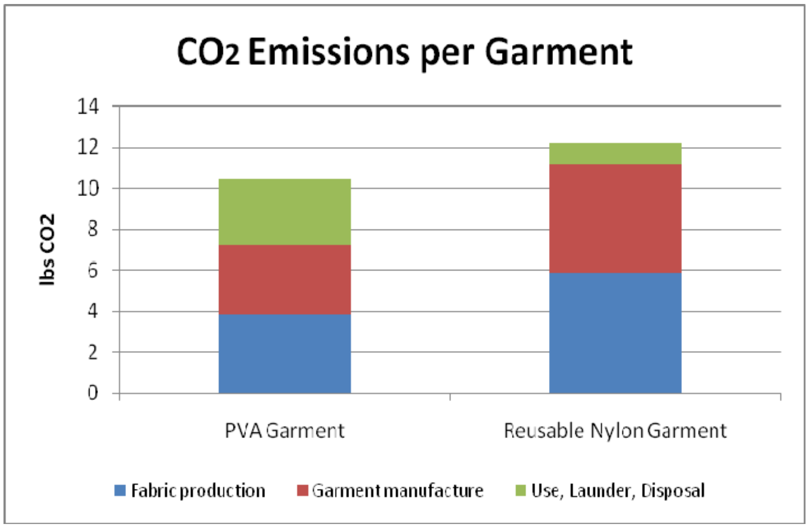
Assumptions for Fabric Production	
	Energy use is 38.5 kwh per kg fabric (based on nylon)[28]
	Water use is 175 gal per kg fabric (based on nylon)[27]
	CO_2 emissions are 6.5 kg per kg fabric (based on nylon)[27]
Assumptions for Garment Manufacture	
	Energy use is 20 kwh per kg garment (based on polyester)[29,30]
	Water use is 0.2 gal per garment (based on polyester)[28]
	CO_2 emissions are 5.8 kg per kg garment (based on polyester)[28,29]
Assumptions for PVA Dissolution Process	
	Batch size is 120 lbs
	Water use per batch is 500 gal. (based on size of solution tank)
	Heater efficiency is 70%
	Two batches per day run at facility
	Starting temperature is 68 °F, ending temperature is 210 °F
Assumptions for Laundering Process	
	Laundry per facility is 1,549,736 lbs/year
	Typical load is 400 lbs
	Water use is 3 gal/lb of garments
	Garment reused 100 times (laundered 98 times) before disposal
General Assumptions (applicable to both sets of calculations)	
	Weight of individual PVA garment is approx. 266 gm*
	Weight of individual reusable nylon garment is approx. 411 gm*
	1 kWh is equivalent to 1.28 lbs CO_2 production
	1 kWh equals 3,414 BTUs

*Based on measured weights of three garments

[27] Functional unit of 100 garment uses; where one reusable conventional nylon multiple-use garment (washed 98 times) = 100 PVA single-use garments
[28] Boustead 2005
[29] Ponder 2009
[30] Franklin Associates 1993

When the cumulative energy use for fiber and fabric production; garment manufacture; and use, launder and disposal were evaluated on an individual-garment basis, energy use was greatest for each garment type during fiber and fabric production, and lowest during use, laundering, and disposal. Water use was also greatest during fiber and fabric production, but was lowest during use, laundering, and disposal. Water use was also greatest during fiber and fabric product, but was lowest during garment manufacture. Although cumulative CO_2 emissions were comparable between the garment types, contributions from each aspect of the LCI varied. Comparable CO_2 emissions would be released during fiber and fabric production and garment manufacture for the nylon multiple-use garment, while releases during use, launder, and disposal would be lower. For the PVA single-use garment, CO_2 emissions would be highest during dissolution of the garment, and lower but comparable during fiber and fabric production and garment manufacture. Differences in energy and water use and in greenhouse gas emissions from manufacture between the garment types are due to the comparatively heavier weight of the launderable garment.





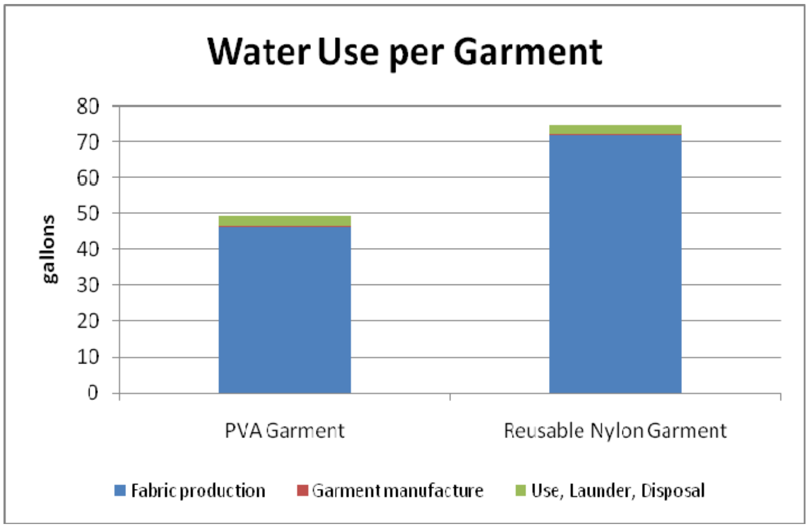
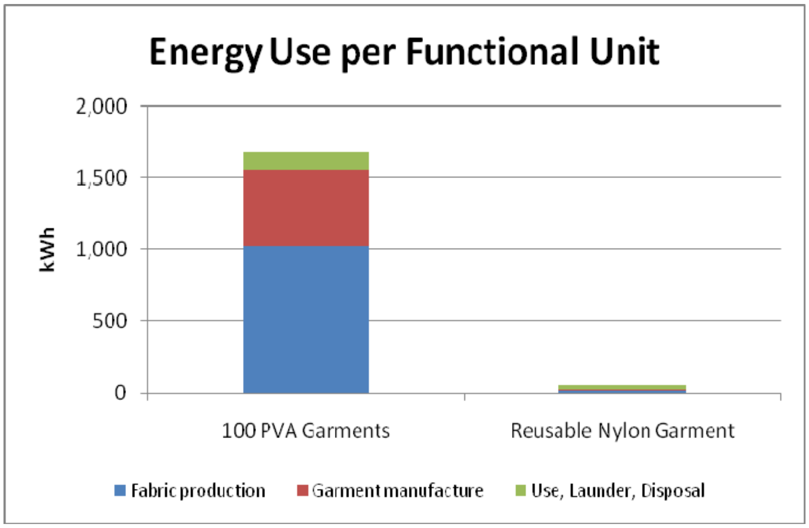
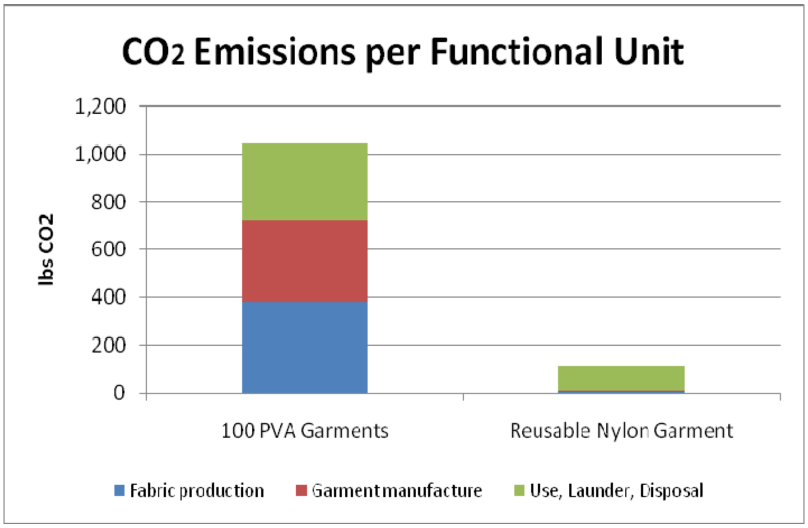


Figure 2. Summary of calculations on a per-garment basis

When energy and water use and CO2 emissions were calculated for each garment type on a functional unit[31] basis, results for all three elements were significantly greater for the PVA single-use garments (Figure 3). Energy and water use would be highest for both garment types during fiber and fabric production, while CO2 emissions would be highest during use, launder and disposal.

31 Functional unit of 100 garment uses; where one reusable conventional nylon multiple-use garment (washed 98 times) = 100 PVA single use garments.





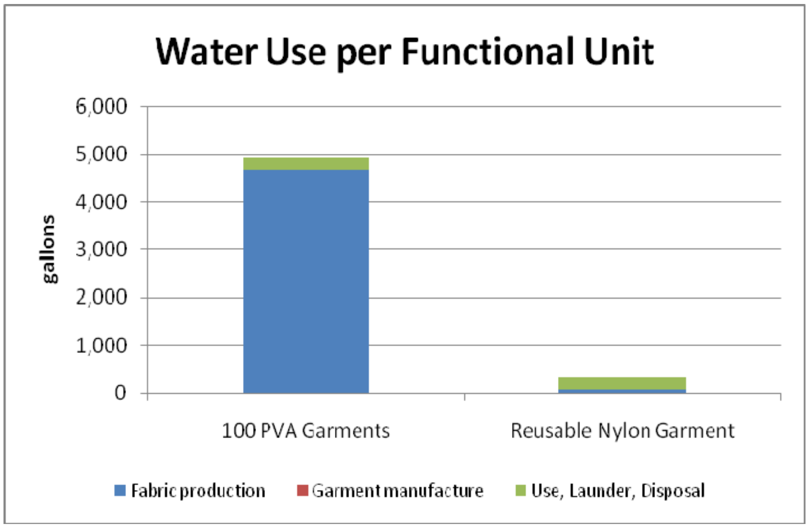


Figure 3. Summary of calculations on a functional unit basis

Converting energy use to greenhouse gas equivalency (Table 2),[32] the nylon multiple-use garment would have a calculated greenhouse gas emission of 50.8 lbs of CO_2 equivalence on a per-garment basis, and 206.3 lbs of CO_2 equivalence on a functional unit basis. The PVA single-use garment would have a calculated greenhouse gas emission of 37.0 lbs of CO_2 equivalence on a per-garment basis, and 3,702.4 lbs of CO_2 equivalence on a functional unit basis.

Table 2. Energy and water usage and CO_2 emissions calculations

	PVA Single-Use Garment	Nylon Reusable Garment
per Garment		
Energy use (kwh)	16.8	24.4
Energy (lbs as CO_2 equivalent)	26.6	38.6
Water use (gals)	49.2	74.8
CO_2 emissions (lbs CO_2)	10.4	12.2
Total greenhouse gas equivalents	37.0	50.8
per Functional Unit*		
Energy use (kwh)	1680.3	60.1
Energy (lbs as CO_2 equivalent)	2660.0	95.2
Water use (gals)	4919.4	339.2
CO_2 emissions (lbs CO_2)	1042.4	111.1
Total greenhouse gas equivalents	3702.4	206.3

*Functional unit of 100 garment uses; where one reusable conventional nylon multiple-use garment (washed 98 times) = 100 PVA single-use garments

[32] http://www.epa.gov/RDEE/energy-resources/calculator.html

Results and Implications

Based on the calculated energy and water usage and CO_2 emissions, the PVA single-use radiological protective garments would have an environmental footprint approximately 18 times larger than the conventional nylon multiple-use garments during the life cycle phases of fiber and fabric production; garment manufacture; and use, laundering, and dissolution. Relative differences between the garment types for the individual elements and the overall environmental footprint for this portion of the LCI are dependent on the degree to which the assumptions and associated calculations represent actual fiber and fabric production and garment manufacturing processes and actual operating conditions in both types of facilities. Additional elements of the LCI associated with raw-material acquisition and resource consumption, transportation, and waste treatment would add additional energy and water consumption and greenhouse gas emissions to the levels calculated for this portion of the life cycle of these products.

Evaluating the two garment types based on functional unit demonstrates that, as wear life of the reusable garment increases, the corresponding per-use environmental footprint of the product gets dramatically smaller relative to the disposable product counterpart. Increases in the number of times a reusable garment is used before disposal decreases the amount of energy, water, and greenhouse gas emissions attributable to each use. Conversely, the resource consumption and emissions attributable to use of a single-use garment is fixed. Thus, insofar as resource extraction and manufacturing is concerned, the reusable nylon garment would enjoy a marked advantage in terms of sustainability over PVA single-use garments. These results are consistent with LCI study results obtained from evaluations of textile products and health-care garments,[33,34,35,36] which also have lengthy wear lives. The results generated during this study show more pronounced differences between the garment types than have been demonstrated for reusable diapers (nappies), which have much shorter wear lives. This is due both to the differences in wear life and also to the fact that the two garments in this study share similar methods of manufacture, while the manufacturing techniques for disposable diapers focus on producing a diaper that is low in resource consumption and, therefore, cost.

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[33] Kalliala
[34] Lehrburger and Mullen 1992
[35] Kalliala and Nousianinen 1999
[36] Ponder 2009

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