Business for Social Responsibility

Apparel Industry Life Cycle Carbon Mapping

Prepared by Business for Social Responsibility

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Introduction

Business efforts are increasingly focused on understanding and addressing greenhouse gas (GHG) emissions. As these efforts mature, greater attention is being focused on GHG emissions throughout company value chains and product life cycles, from raw material extraction to disposal, as a complement to company-specific carbon footprinting. Reasons for this focus include an interest among companies in improving communications with consumers and others, a desire to reduce GHG-related risks throughout the value chain, and a potential need to address future product labeling requirements.

Within this context, BSR and H&M initiated a project to bring together current publicly-available information about the life cycle carbon emissions of the apparel industry through a review of existing research. This was conducted with two goals in mind:

1) To develop a general overview of GHG emission "hotspots" in the life cycle of a variety of garments, which will enable initial prioritization of areas for action and further data collection.
2) To promote sharing of resources among apparel industry peer companies, to enable deeper analysis and potentially greater collaborative action.

Toward these ends, BSR personnel and a team of University of Michigan sustainable business graduate students conducted a three-pronged approach to research and analysis, as follows:

1) *Collection and analysis of public findings.* This was done through a scan of publicly-available secondary sources such as life cycle assessment (LCA) studies, with a focus on finding information about a variety of fibers and garments.
2) *Collection and analysis of peer knowledge.* Publicly-available apparel company data was gathered, and additional data was solicited directly from companies.
3) *Expert interviews*. Experts in apparel life cycle assessment were interviewed to allow better understanding of the types, strengths and shortcomings of available data.

Life Cycle Approach

This study focused on gathering information about GHG emissions from activities along the full life cycle of individual garments, from raw material acquisition through disposal (see Exhibits 1 and 2 for life cycle stages of natural and synthetic textiles). Available data varies substantially in granularity, with some providing emissions data for large segments of a garment's life cycle (e.g. "textile manufacturing" or "consumer use"), while others provided data for smaller segments (e.g. washing, drying and ironing within the consumer use stage).

The LCA approach is extremely useful for providing accurate information about narrowly defined systems, but such studies have substantial constraints and limitations. The data collected in this study are not likely to fully reflect the unique production circumstances of a given garment produced today. There may be substantial differences in electricity sources, travel, production processes, clothing use, or other areas. LCAs must also establish boundaries for measurement which may vary from study to study, and some impacts such as land use change may not be included in all studies. In addition, some of the information collected is dated, and production processes may have changed over time. Finally, it should be noted that this particular review focuses on greenhouse gas emissions, and does not explore non-GHG environmental or social impacts in the apparel industry value chain, some of which are considerable.

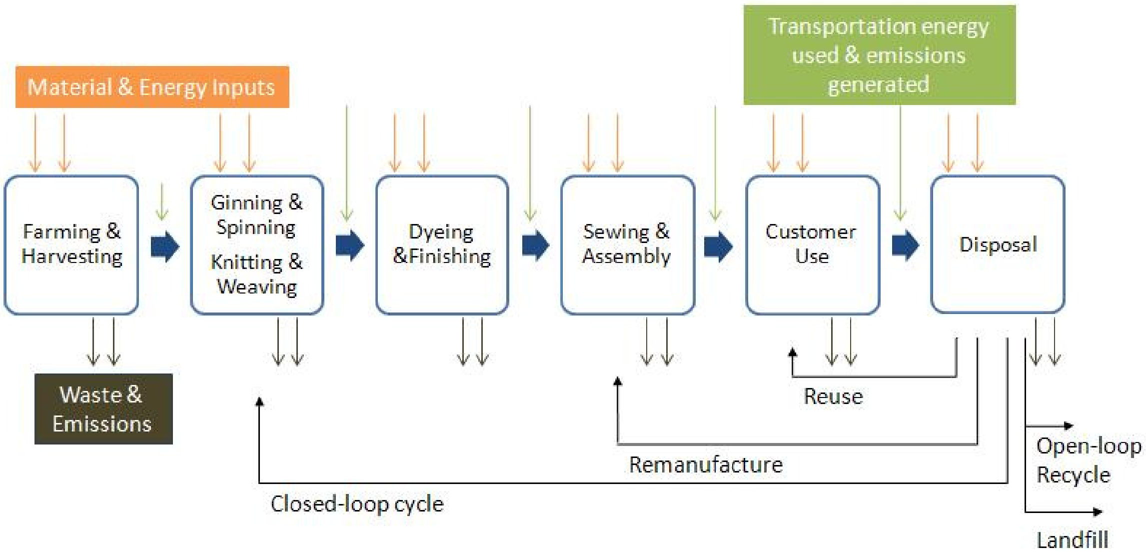


Exhibit 1: Natural Textile LCA Diagram

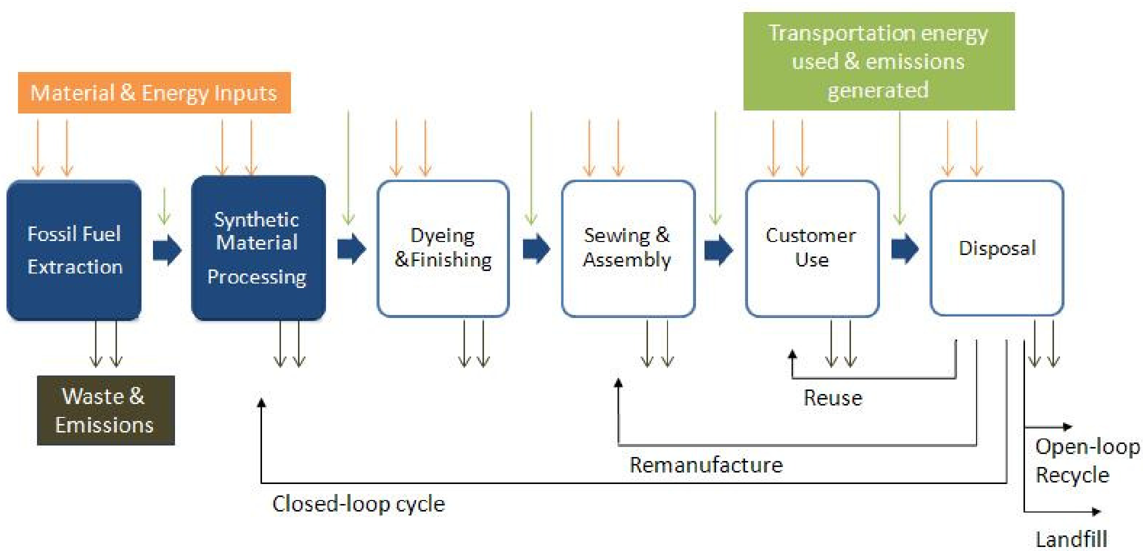


Exhibit 2: Synthetic Textile LCA Diagram

Key Findings

Primary Carbon Hot Spot: Use Phase
The single most important factor determining a garment's life cycle GHG emissions is use-phase care. Most studies noted that laundering is the largest contributor to a garment's life cycle GHG footprint, although there are some limited exceptions. Key points include:

- Garments requiring washing, drying and possible ironing require the largest energy inputs during the use phase. As a result of these energy inputs, laundering accounts for 40-80% of total life cycle GHG emissions for such garments.
- Machine drying is generally the single largest energy user and cause of GHG emissions in garment life cycles.
- Use of low-GHG energy sources such as renewable or nuclear power for laundering dramatically reduces garment life cycle GHG emissions.
- Garments that require hand-washing are likely to have much lower use-phase energy use and resulting GHG emissions.
- Garments requiring dry-cleaning may have lower use-phase GHG emissions than those requiring traditional laundering, but actual results are likely to depend on consumer behavior.
- Several studies indicated that garments are often laundered more frequently than necessary (e.g. after every use), which substantially increases total GHG emissions.

Secondary Carbon Hot Spot: Raw Materials
The second most important factor determining a garment's GHG emissions is fiber type:

- Synthetic fibers have comparatively high GHG emissions as a result of energy use required for raw material production.
- Wool has comparatively high GHG emissions as a result of methane emissions from sheep
- Plant fibers such as cotton or linen have comparatively low GHG emissions from production, with linen having substantially lower production-phase emissions because of its comparatively low need for pesticides, fertilizers and irrigation.

Fiber type may also affect use-phase care in several ways:

- Some fibers, such as wool, should be dry-cleaned or hand-washed rather than machine washed and dried
- Some fibers, such as linen, are more likely to be ironed
- Some fibers retain less moisture from washing than others (for example, polyester retains less than cotton), and as a result needs less energy to dry. However, this is only relevant if the drying process is adjusted according to fabric type.

Other factors determining GHG emissions

- *Sourcing and manufacturing locations*. GHG emissions vary by sourcing and manufacturing locations, for example as a result of differing energy sources or required activities such as irrigation. The information available for this survey, however, did not quantify differences among locations for specific materials.
- *Dyeing*. No studies were found that distinguish the energy use and GHG emissions from different dyes for various fabric types. According to apparel LCA expert Dr.

Olivier Jolliet, the dyeing stage in textiles has little impact on the overall energy and GHG footprint, but a forthcoming LCA study of a viscose dress suggests dyeing may cause as much as 19% of life cycle GHG emissions for that garment. Despite this uncertainty, some generalizations can be made about dyeing intensity. For example, many studies point to dyeing as being very water intensive. Many dye applications require use of hot water, the heating of which is an energy intensive process. For example, polyester cannot be dyed below 100 degrees Celsius, which means higher energy consumption and thus more GHG emissions than dyeing other fibers. Also, one source notes that dark shades require more rinsing and dyeing than light shades, and thus consume more energy.

- *Assembly.* Garment assembly was rarely touched on in LCA studies and literature reviewed.
- *Packaging.* According to several studies, packaging has a limited GHG impact, in part because packaging is often composed of reused or recycled materials. Packaging impacts generally do depend greatly on type of garment, but may differ by retailer or delivery method.
- *Transportation.* Most studies found transport to be a small portion of a garment's total carbon footprint. However, this is typically based on an assumption that long distance transportation is predominantly ship-based, with no air transport involved. If air transport is used during any portion of a product's manufacture or distribution, it is likely to drive up GHG emissions substantially. In addition, several studies noted that road transport has substantially greater impacts than long-distance ocean transport.
- *Consumer transport.* Consumer transport is generally left out of garment LCA studies, in part because it is extraordinarily variable, and partly because it is potentially very large. A recent LCA study notes that "a 15 km round-trip journey in a passenger car results in 5-6 kg of carbon dioxide emissions, on the same order of magnitude as the total for the other cotton T-shirt processes." (Steinberger, Friot, Jolliet & Erkman. "A Spatially-explicit Life Cycle Inventory of the Global Textile Chain," *The International Journal of Life Cycle Assessment*, Springer Berlin/Heidelberg, May 2009.)
- *Garment lifespan.* Short garment lifespans can drive up total GHG emissions in ways that are not accounted for in typical garment LCAs. To illustrate using extreme examples, the life cycle GHG emissions of a garment that is used and laundered once before being discarded will be very low compared to the life cycle emissions of a comparable garment that is used and laundered 100 times, but the emissions *per wearing of the garment* are much higher for the first item.
- *Garment disposal.* LCAs demonstrate that GHG emissions related to garment disposal are very small, and generally result from small amounts of methane created during decomposition of natural fibers. Certain disposal options reduce GHG emissions, however. Incineration of natural fibers in a waste-to-energy plant may displace the use of fossil fuels, for example, while the recycling of used garments into new textiles reduces the need for new raw materials.

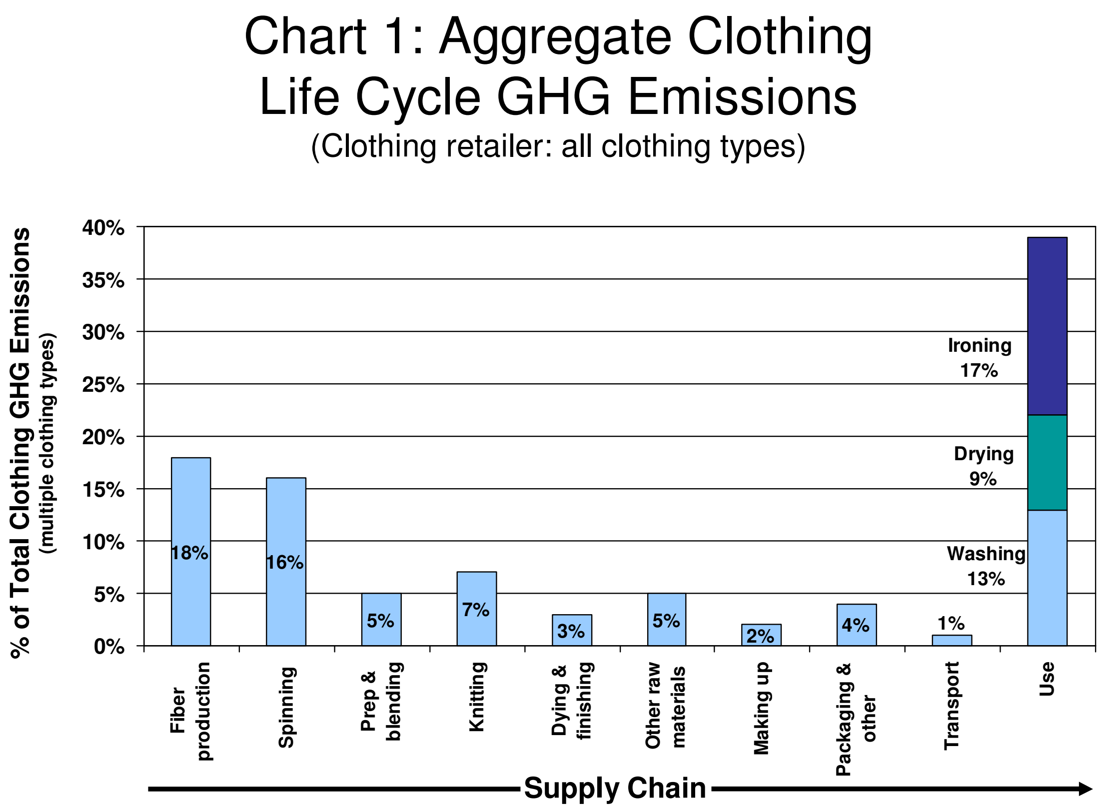
Detailed Analysis[1]

In this section, we examine some of the available data in more detail, conduct comparisons across types of activities, and provide GHG emissions or energy use 'heat maps' of several specific garments for which sufficient data is available. Note that this is not intended to be an exhaustive list of available garment LCAs, but focuses on presenting a range of fiber and garment types.

Aggregate Life Cycle GHG Map: Multiple Clothing Types

Chart 1 shows one large clothing retailer's estimated life cycle GHG emissions from the garments it sells. These impacts are a very good reflection of most publicly-available studies, which identify key GHG sources at the start of the clothing life cycle in fiber production and spinning, and at the end of the life cycle in the consumer use phase. Consumer use produces more GHG emissions than any other segment of the aggregate life cycle as a result of energy used to wash, dry and iron garments.

Although this provides a good overall picture of aggregate GHG emissions from clothing, the actual GHG emissions profile will be different for any given garment, and other retailers' aggregate emissions are likely to vary depending on the type of clothing sold.

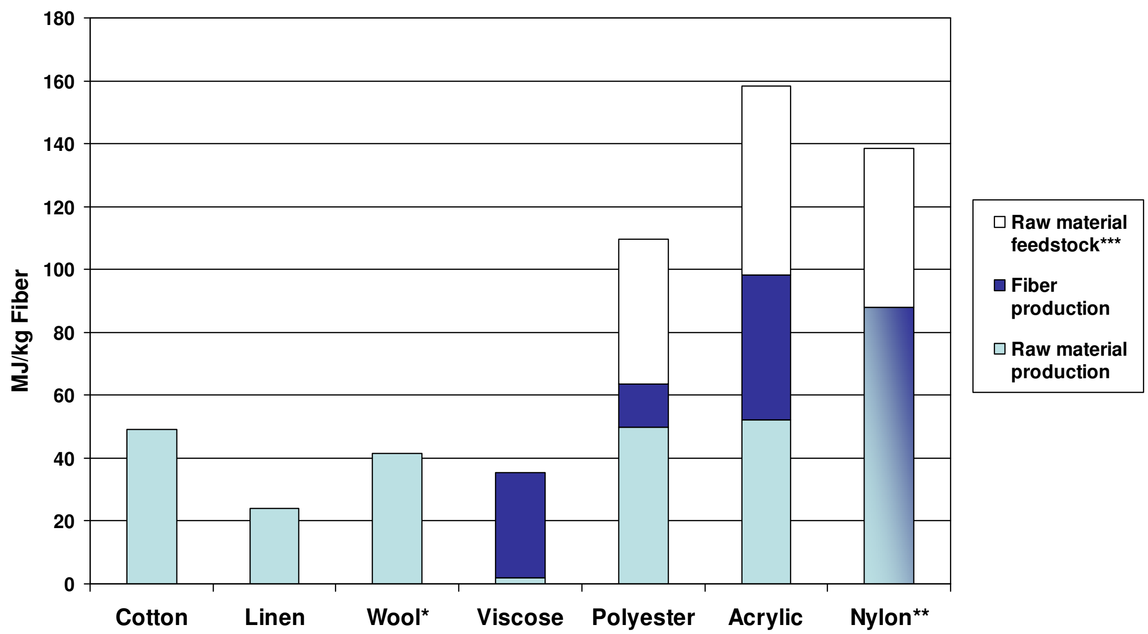


[1] Note that tables in this section use various units, corresponding to the data available. In some cases, life cycle GHG emissions are reported as a % of total emissions a proportion of a specific baseline, while in others data might be reported in energy units or units of CO_2 equivalent.

Fiber Production

Chart 2a highlights the energy used to produce various types of natural, man-made and synthetic fibers, before the fiber is spun into yarn. Energy use provides a reasonable approximation for GHG emissions in most cases, as most emissions result from combustion of fossil fuels to produce energy. Comparing energy use may also provide a truer comparison among fiber types, because GHGs will vary by energy source (so, for example, electricity required to produce polyester fiber may be produced from coal-fired power plants in China emitting 1 kg CO_2/kWh, or hydroelectric plants in Brazil emitting virtually nothing).

Chart 2a: Comparative Energy Use in Fiber Production



Sources: See Appendix B.
*Methane emissions omitted.
**Bottom segment for Nylon includes both fiber production and raw material production
***Energy used for raw material feedstock does not generate GHG emissions during production

There are two significant points where energy use in fiber production does not reflect GHG emissions. First, methane emissions from sheep are a large but highly uncertain source of GHGs. Estimates of methane emissions reviewed for this study varied per sheep vary from 5 kg/head/year to 19 kg/head/year. In addition, some of the GHG emissions from raising sheep can be attributed to other sheep products, such as meat.

Second, the energy content of fossil fuel feedstocks used to produce polyester, acrylic, and nylon are included in the data (although highlighted separately). These feedstocks do not create GHG emissions during production, because they are not combusted and thus do not produce CO_2 (however, they may generate CO_2 emissions if the garment is incinerated, for example after disposal). It should also be noted that 'fiber production' is not relevant for naturally-occurring fibers that do not need to be manufactured.

Chart 2b: Comparative GHG Emissions from Fiber Production (vs. Wool)

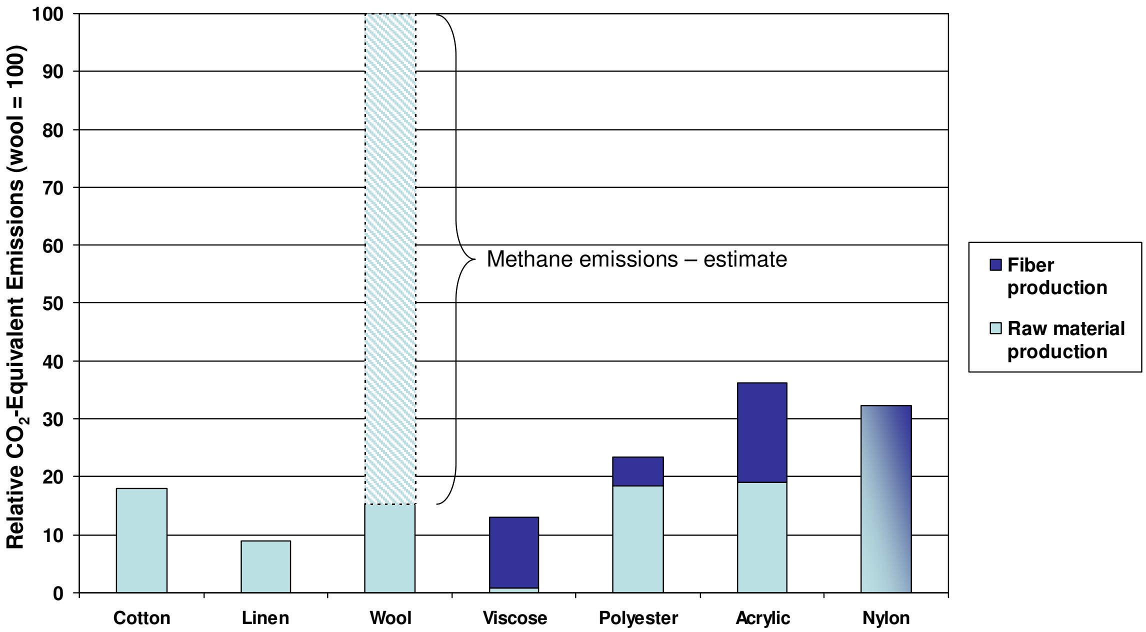


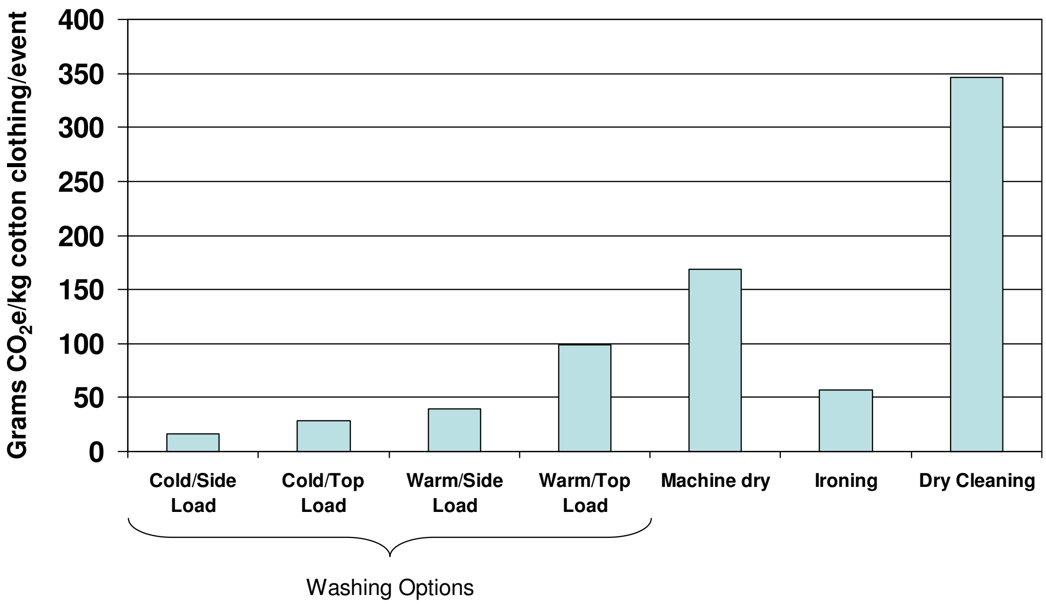
Chart 2b uses the energy data from Chart 2a, plus additional data to benchmark the estimated GHG emissions from production of the various fibers against the emissions from wool. Linen is the clear low-energy (and hence, low-GHG emissions) material in the fiber production phase. This is a result of substantially lower fertilizer and pesticide use than for cotton, and less production energy required than for manmade fibers. In general, plant-based fibers require less energy to produce than manmade fibers, and viscose (produced using a natural feedstock) requires less energy than synthetic fibers. Wool is by far the highest GHG emitter during this stage of the life cycle, as a result of methane emissions. For further discussion of these fibers, see the following sections.

Note that much of the data in Charts 2a&b are over ten years old, and some production processes may have changed during that time.

Use Phase

Chart 3 compares the GHG impacts of various types of laundering in the use phase of a garment. Direct GHG emissions are given as grams of CO_2 per kg of cotton clothing per event ('event' being a single wash, dryer cycle, ironing, or dry cleaning). Four different options for washing are given based on water temperature (cold or warm) and machine type (side or top load). Note that consumer travel to and from a dry cleaner or laundromat is not included in this analysis, but would result in significant additional GHG impacts.

Chart 3: Use Phase Care Options: Comparative GHG Emissions Per Event



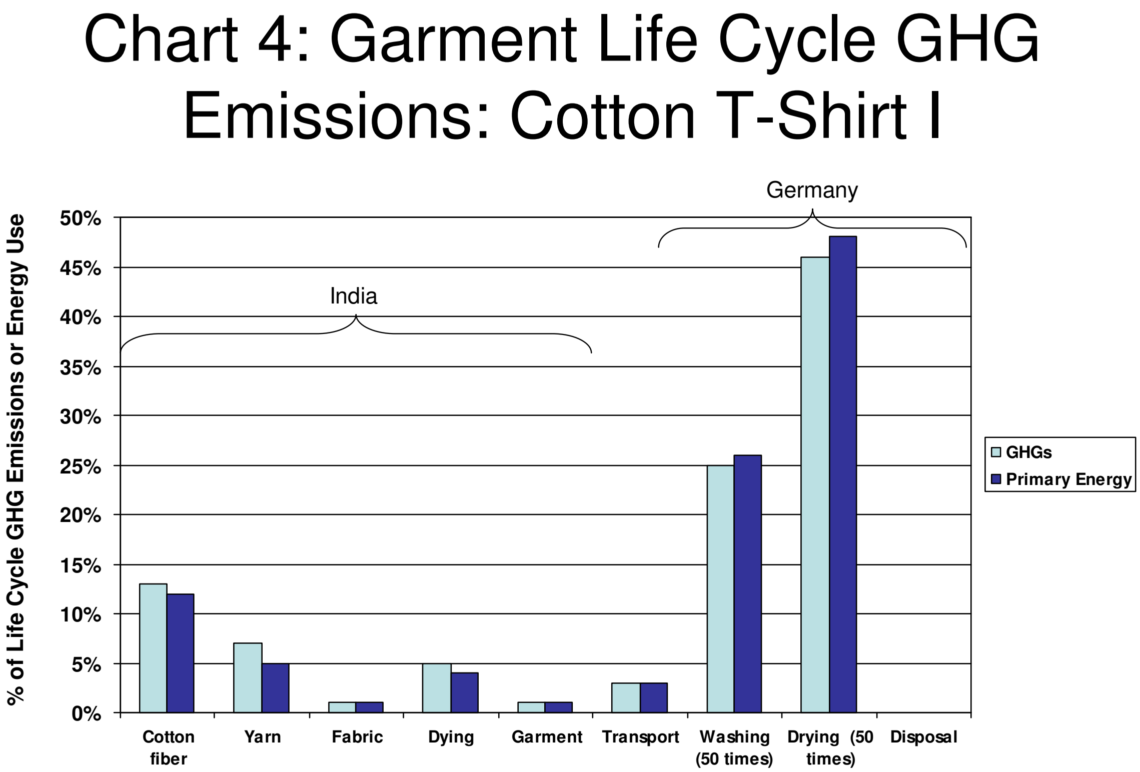
Sources: See Appendix C

Dry cleaning generates the greatest GHG emissions per event, but it should be noted that the high per-event emissions from dry cleaning do not necessarily indicate that dry cleaned clothing generates greater use phase GHG emissions than non-dry cleaned clothes. Dry-clean only clothing may be laundered less frequently than clothing that can be cared for at home.

Type of washing machine and choice of water temperature have clear impacts that cause emissions to vary from 11g CO_2 for cold water in a side load machine, to 64g CO_2 for warm water in a less efficient top load machine. Drying and ironing are two optional activities that can also vary (although such variance was not captured in available data) based on temperature setting and length of time.

Fiber and garment type is not considered in this analysis, although it has clear impacts on GHG emissions. Some garments require hand washing or air drying, for instance. Various fiber types also require different amounts of energy to launder: Cotton, for example, requires more energy to dry than polyester, but less energy to iron than linen.

Garment 1: Cotton T-Shirt
One of the garments with the most available life cycle data is the cotton T-shirt. Specific studies vary based on a range of factors, but typically agree that the garment use phase produces the highest GHG emissions, while emissions from raw material production are also significant.

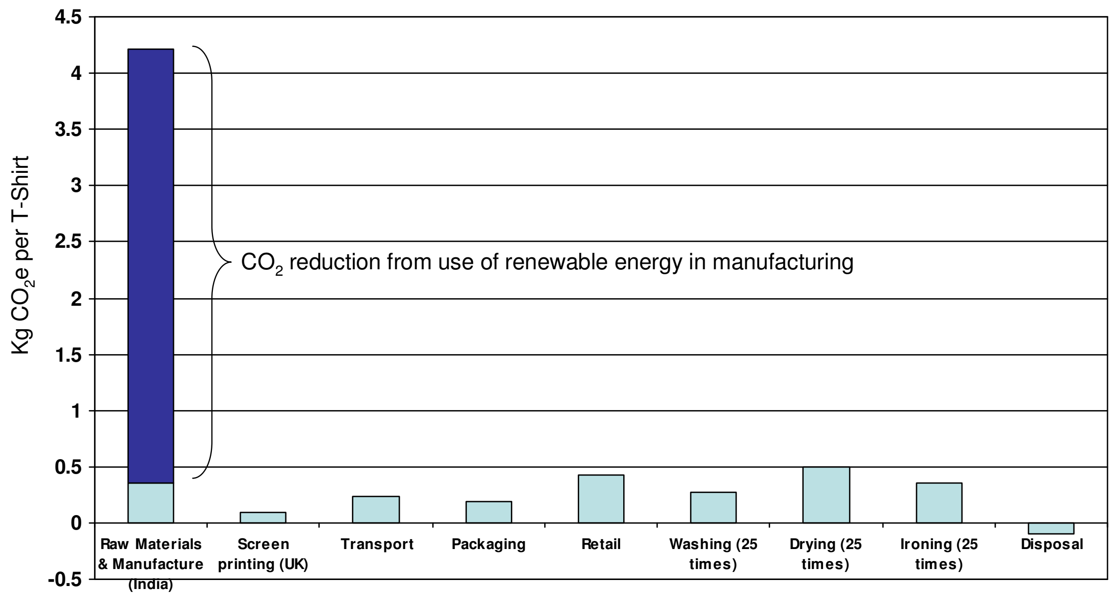


Source: Steinberger, Friot, Jolliet & Erkman. "A Spatially-explicit Life Cycle Inventory of the Global Textile Chain," *The International Journal of Life Cycle Assessment*, Springer Berlin/Heidelberg, May 2009.

Chart 4 shows some of the results of a recent study soon to be published in the *International Journal of Life Cycle Assessment*. T-shirt fabric and garment production are shown to be the least GHG-intensive portions of the garment's life cycle, aside from disposal. This figure also demonstrates the rough equivalence between energy use and GHG emissions in the garment life cycle.

Chart 5 provides an alternate look at GHGs in the T-shirt life cycle, showing amount of CO_2 per stage, as well as significant improvements that have been made by using renewable energy in manufacturing processes. There are several other substantial differences between these two studies, including number of times the garment is washed (50 in Chart 4 and 25 in Chart 5), and the inclusion of retail impacts and ironing in Chart 5.

Chart 5: Garment Life Cycle GHG Emissions: Cotton T-Shirt II

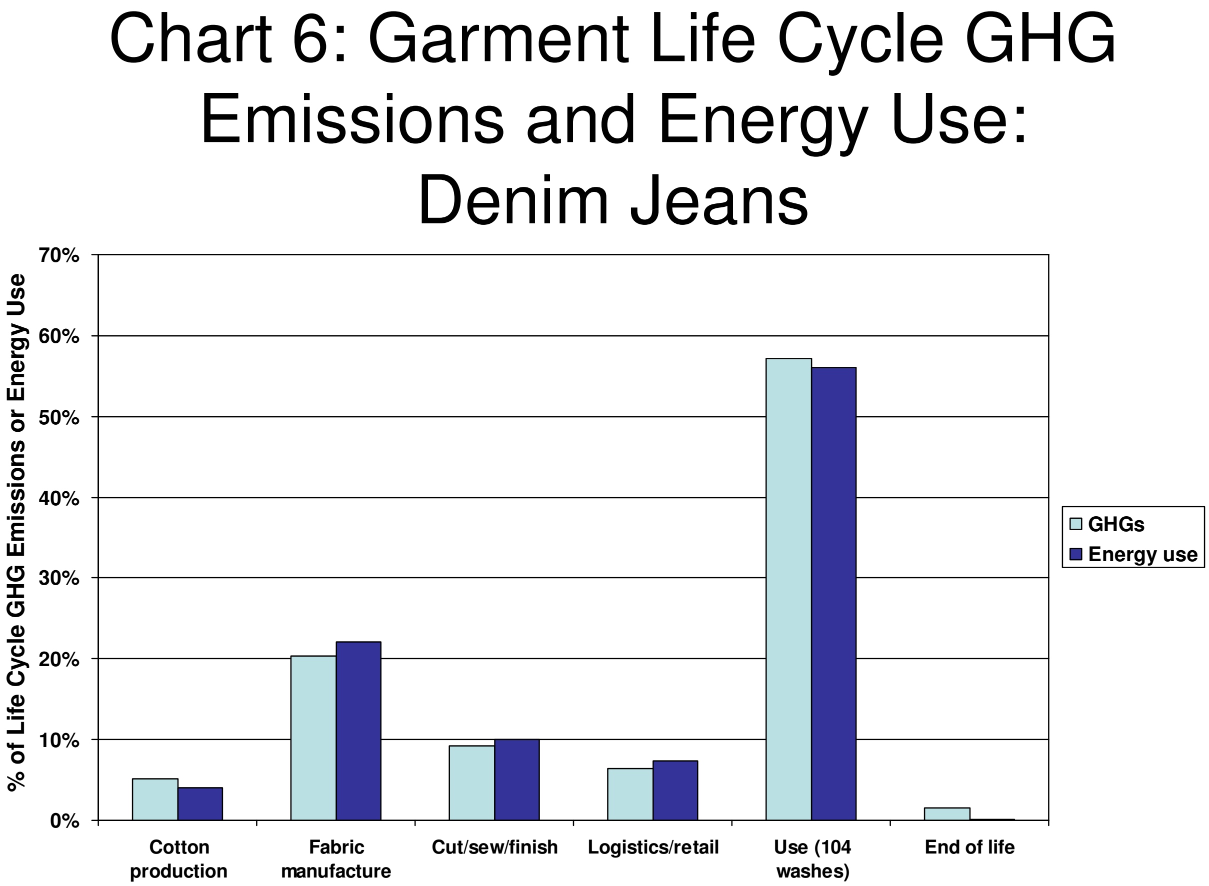


Source: Continental Clothing, "The Carbon Footprint Of A Cotton T-shirt," Executive Summary. http://www.continentalclothing.com/?module=cms&P=382

Use phase is again the most significant cause of GHG emissions, generating nearly 50% of the actual total. If renewable energy is not used in raw materials and manufacturing, however, use phase GHG emissions would be less than 20% of the total for this garment. This may still be the single largest life cycle GHG impact if each step in raw materials and manufacturing are broken out separately, but it is a much lower percentage than most other garment LCA studies. This may in part be a result of using relatively clean energy from the U.K. grid during use, while using coal-generated energy during manufacture in India. As of this writing, the project team only has access to the executive summary of this LCA, so we are unable to conduct a full comparison and analysis if this issue.

Another notable point in this LCA is that disposal results in a small decrease in GHG emissions. This is likely to be a result of either incineration of the garment in a waste-to-energy facility or recycling of the garment fibers.

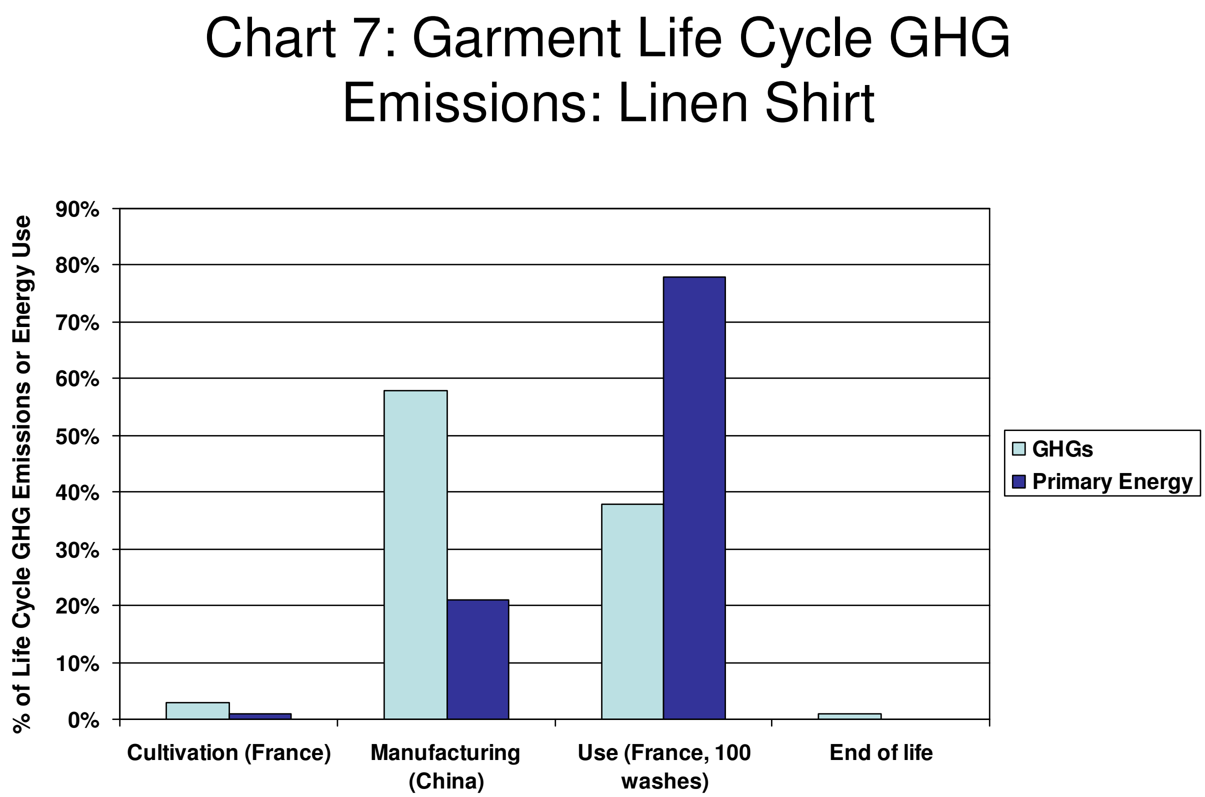
Garment 2: Denim Jeans
Chart 6 shows the relative life cycle GHG emissions from a pair of denim jeans. The number of washings is double that of the T-shirt in Chart 4, which helps increase the relative size of use phase emissions. Cotton production is a much smaller percentage of total GHG emissions than for the T-shirt, in part because of the increase in use phase emissions, as well as the greater GHG emissions from denim fabric manufacture and finishing due to dyeing and other processes.



Data source: Levi Strauss & Co.

Garment 3: Linen Shirt
Chart 7 illustrates the relative GHG emissions generated by a linen shirt. It demonstrates that primary energy is not always a good proxy for GHG emissions, depending on the details of the system studied. In this case, the use phase occurs in France, where low-GHG emitting nuclear power is the dominant energy source, while manufacturing occurs in China, where high-GHG coal-fired power plants provide most electricity. Note that if manufacturing and use phases utilized comparable energy sources, then the GHG impacts would likely reflect primary energy use – in other words, the use phase would generate the largest emissions.

Chart 7 also shows that the cultivation of raw material (flax) is a smaller percentage of life cycle GHG emissions and energy use than it is in a cotton T-shirt. This is because of both linen's smaller GHG emissions during cultivation (as shown in Chart 2), as well as the higher use-phase energy required to iron linen.

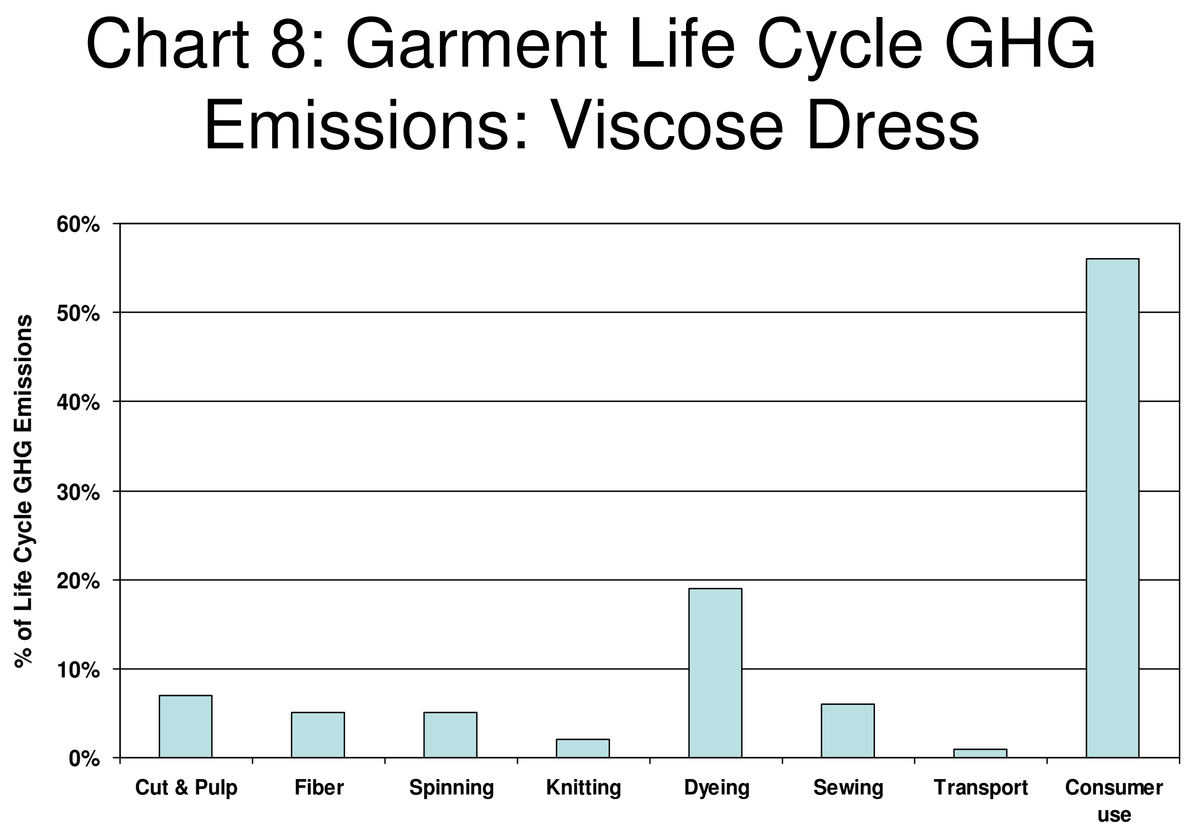


Source: Masters of Linen Present "The Linen Shirt Eco-Profile." www.mastersoflinen.com.

Note that the source of this study, Masters of Linen, is a subsidiary of the European Flax and Hemp Confederation (CELC), and one of the outcomes of the study was a demonstration demonstrate that linen clothing is environmentally preferable to cotton. Given this source, however, there is some possibility of bias in the LCA results.

Garment 4: Viscose Dress

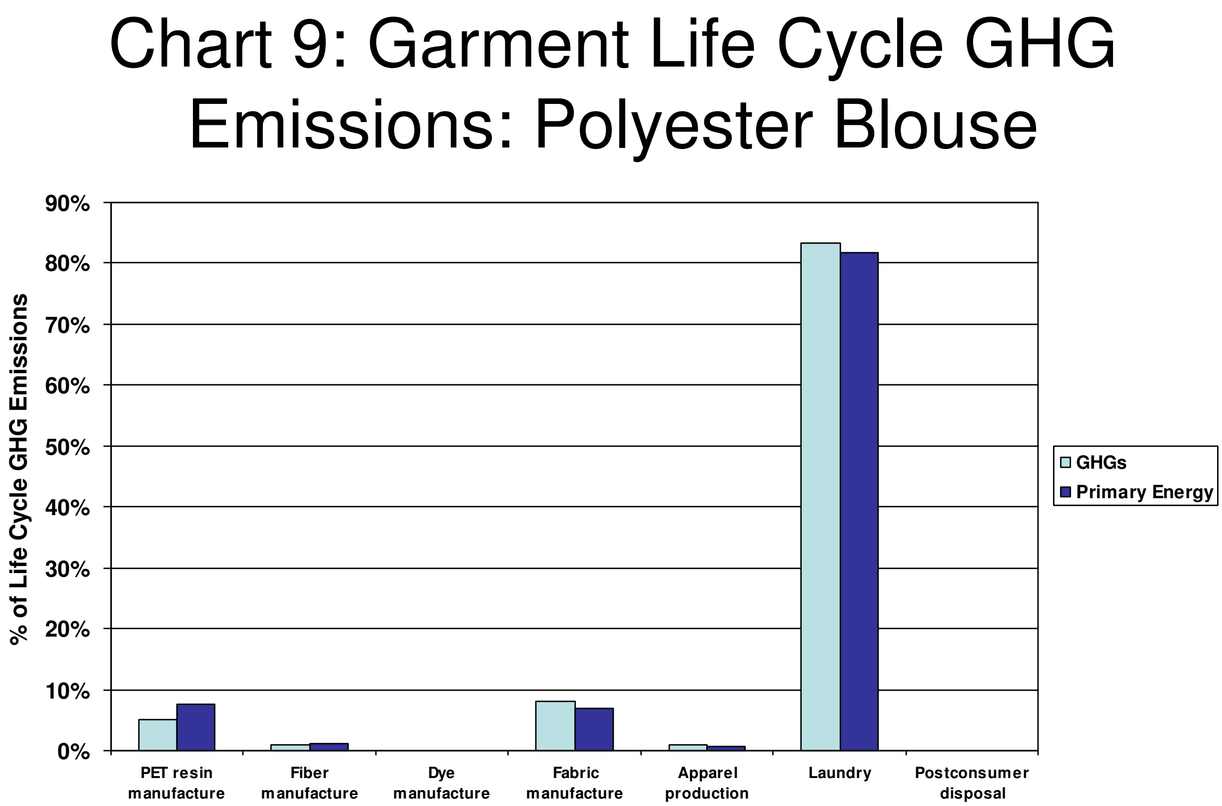
Chart 8 illustrates the estimated life cycle GHG emissions from a viscose (bamboo feedstock) dress. The original industry study notes that a significant amount of secondary data was used in this analysis, particularly for bamboo pulp, fiber production, and garment use.



As with the garments above, the consumer use phase dominates dress's life cycle emissions. Dyeing (charcoal in color) is relatively more important in this garment than in others, although the study did not suggest why this might be the case.

The May 2008 study on the "International Market for Sustainable Apparel" by Packaged Facts notes that pesticides and other chemical inputs are generally not used in bamboo production, suggesting that bamboo production (prior to processing for fiber) is likely to result in much lower GHG emissions than typical methods of cotton production. However, Packaged Facts and other sources also note that other manufacturing stages have significant chemical and energy use impacts. These points are reflected in the Danish Environmental Protection Agency findings included in Charts 2a and 2b, above, which show very low energy requirements for bamboo cultivation, and much larger energy needs for fiber production from the bamboo feedstock.

Garment 5: Polyester Blouse
Chart 9 illustrates a classic, early garment LCA conducted by Franklin Associates in 1993 for the American Fiber Manufacturers' Association reviewing, which reviews a polyester blouse.



Source: Franklin Associates, 1993 LCA for the American Fiber Manufacturers' Association: http://www.fibersource.com/f-tutor/lca-page.htm

Once again, use phase impacts dominate, in this case even more so than in the other garments above. The study notes that use-phase impacts vary significantly with consumer preferences and habits, but assumes that the garment is worn twice before washing, and although no distinction is made between GHG impacts from washing and drying, washing at 94 degrees F with cold rinse requires over 70% of total laundry energy use, while drying in a machine for 15 minutes (no temperature given) requires just over 30%. This is different from most other textile LCAs, which typically demonstrate that drying requires greater energy than washing. This may be due in part to the fact that polyester requires less energy to dry than some other fibers, including cotton. This result, as well as the comparatively high use phase GHG emissions, may also be a case where technology has changed over the past 15 years, perhaps as a result of increasing efficiency standards for laundry equipment.

Within the overall manufacturing process, PET resin manufacture and fabric manufacture (including texturizing, knitting, dyeing, and finishing) are the most significant GHG emitters, while apparel production produces a very small portion of total GHG emissions. Dye manufacture (rather than the dying process itself) also generated few GHGs.

Other Garment LCAs

Men's Cotton Briefs. A relatively detailed study of the energy footprint of men's cotton briefs is given in a 1992 "Streamlined Life Cycle Assessment of Two Marks & Spencer plc Apparel Products," authored by Environmental Resources Management (ERM). The study is available at www.satradingco.org/Reports/LCA_Final.pdf. Consumer use is responsible for 80% of total life cycle energy consumption, while cotton fiber results in only 3% and product manufacture in 13% of energy use. Over 30% of energy used in product manufacturing is used in yarn production.

Polyester Trousers. The same ERM study provides a detailed energy footprint of polyester trousers. Consumer use results in 76% of total life cycle energy consumption. Polyester fiber manufacture is responsible for 7% of the total, and product manufacture for 13%. 35% of energy used in product manufacturing is used in yarn production.

Polyester Jacket. The Steinberger et al. study used as the source for the T-shirt data in Chart 4 also provides a life cycle assessment of a polyester jacket. It finds product manufacture responsible for 72% of total GHG emissions and use phase responsible for 27% of emissions, although it should be noted that jackets are laundered much less frequently than many other garments. Key GHG sources included fabric production (33% of total emissions), yarn (22%), and resin production (15%).

Other Fibers

Although the study team did not find sufficient data on other fibers of interest to plot full garment life cycle GHG impacts, limited data was found on several of them, as follows:

Nylon. According to the source used for Chart 2a, nearly 140 MJ of energy is used per kg of fabric produced, including 50 MJ of feedstock energy (which does not generate greenhouse gases). Potent nitrous oxide (GHG) emissions are also produced during nylon production, which in the case of one plant in the 1990s may have had an impact equivalent to over 3% of the UK's entire CO_2 emissions. A study of nylon carpets concludes that raw material acquisition is the most intensive stage, (Well Dressed) but carpets would not take into account the use phase effects of garment laundering.

Acrylic. The DEPA study states that 157 MJ of energy is used per kg of fabric produced (although 60 MJ is energy feedstock that would not contribute to GHG emissions), and that the production of propene, a key precursor to acrylic, produces approximately 0.528 kg CO_2/kg of propene. The study also notes that the spinning step in acrylic fabric production is particularly energy intensive. No other studies were found that analyze acrylic garments.

Wool. Wool production offers a unique problem in allocating energy use or GHG emissions, in that sheep are raised for food as well as wool. The DEPA study used as one source for Chart 2 above chose to allocate 40% of life cycle impacts to wool production but notes that actual allocation may vary substantially, and in Chart 2 we chose to allocate 100% of emissions to wool. The DEPA study was also unable to determine an energy figure for wool scouring, which according to a more recent study on merino wool may be 21.62 MJ/kg wool. Wool sweaters are most likely hand washed or dry cleaned, and probably worn at least several times before being laundered. As a result, use phase impacts for wool sweaters are likely to be lower than for machine-washed and dried garments.

Apparel Company Efforts

While reviewing publicly available information from corporate websites, sustainability reports, and CDP disclosures from approximately 20 apparel companies, we found that roughly half of these companies are addressing their own carbon impacts, while only a few of those are taking steps to shift to a lower-carbon supply chain. The leading companies are demonstrating the following actions needed to successfully find and reduce carbon hot spots in their supply chain:

- Using life cycle analyses (LCAs) to measure GHG emissions across the supply chain.
- Implementing specific supplier standards and/or training engagements to assist suppliers in addressing energy efficiency.
- Helping suppliers track and measure their energy consumption so that suppliers can create targeted goals for reduction.
- Creating carbon footprint or green indexes for their products to inform designers, manufacturers and customers about the environmental considerations of that product.
- Adjusting distribution and logistics to maximize efficiency.
- Aligning with other companies, NGOs or industry organizations to collaborate on supply chain carbon reductions.

Ultimately, what is not measured cannot be managed. For companies to effectively reduce GHG impacts in their supply chains, they must first measure and understand the emissions involved in key processes. No two manufacturing facilities are the same. It may also take a coordinated industry effort to share best practices and transform the supply chain, especially in emerging markets like China and India where many apparel products are made.

Research Gaps

Despite conversations with leaders in the field and extensive review of major journals, gaps in the research remain. Both in terms of methodology and data, the field of life cycle assessment of textiles is evolving.

Methodology
As demonstrated in the data presented above, there are a variety of means for gathering, analyzing, and presenting life cycle data that limit comparability of LCA studies. There have been several publications providing broad guidelines for life cycle assessment, notably the UNEP's Life Cycle Management Study and the British Government's "Guide to PAS 2050: How to assess the carbon footprint of goods and services," and the ISO14040 series is also used for LCA analysis. However, to date, the only framework document specifically targeted to textiles is the DEFRA "Mapping of Evidence on Sustainable Development Impacts that Occur in the Life Cycles of Clothing." This work provides a more specific framework on the methodology and boundaries of a textile LCA. We are told that a US-based equivalent framework will be released by NSF shortly. While we feel comfortable with the boundaries set for both our research and the LCA studies referenced, a change or establishment of the

accepted framework and bounds could alter the requirements for and ultimate results of a bona fide LCA in textiles.

Data

There are several individual studies that have presented life cycle analyses of specific products, but most LCA researchers know that LCA studies are not necessarily comparing apples to apples. This is because the boundaries of the study, assumptions made, and data utilized can all differ. For example, one LCA of a cotton T-shirt (DEPA) stated that nearly 50 MJ/kg is required in the production of raw material, while another study stated that only 21 MJ/kg of energy is needed to produce a cotton T-shirt (EcoTextile News), and the soon-to-be published Steinberger et al. LCA of such a shirt finds that it requires 113 MJ/kg.

Additionally, according to the experts and our findings, certain areas of analysis are more developed than others, while some analyses may be influenced by outside factors. For example, data on transportation and the washing cycle tend to be more thorough and widely available than data about other areas of the supply chain. Other studies, such as the Masters of Linen LCA, come with an agenda and thus must be viewed with an especially skeptical eye.

Not all of the garments researched or LCA stages have the same amount of information available. For example, chiffon/polyester fabric blends has not been studied at all as far as we can tell from literature reviewed, but polyester has. A second example, dyeing, an area with large ecological impact, does not usually have a sizable impact on carbon footprint (it is not energy intensive but the disposal of dyes can have tremendous effect on water) but is a stage with a great deal of uncertainty and worthy of further study. As noted in the data above, some LCAs aggregate portions of the life cycle either to simplify results or often because detailed data is unavailable, while others provide a useful analysis of specific activities.

Recommendations

The recommendations below are given without analysis of any given company's actual supply chain or product mix. These factors must be taken into account before optimal actions to address supply chain GHG emissions hot spots can be taken. Despite this, we feel that the results of this study point in several clear directions.

Areas for GHG reduction

The following activities should be considered to reduce total life cycle apparel GHG emissions:

- *Product Design for Environment.* The most critical life cycle GHG emissions decisions are made in the product design stage, so consideration of GHG and other environmental impacts should be incorporated in design decisions.
- *Care requirements*. Product care requirements and labels should be considered and consumers educated (e.g. through modified care labels or active engagement) so that garments are washed no more than necessary and in a low-impact fashion.
- *Consider enhancing product durability*. More durable products substantially reduce GHG emissions by spreading the "sunk costs" of manufacturing emissions over a longer product life.
- *Review raw materials and engage with suppliers*. consider greater use of plant-based fibers where garment specifications permit, engaging with suppliers to reduce emissions, and shifting types of natural fibers to reduced GHG types (e.g. from cotton to possibly organic cotton).
- *Transport*. If air freight is used at any point in the supply chain, consider options to reduce it.

Data collection

As demonstrated above, data about life cycle GHG impacts in the apparel industry are substantially limited, and often the data that is available is not comparable across garments, fibers, or brands. Such data can also be very challenging and time-consuming to collect. We recommend engaging with suppliers and peers to better understand and compare specific GHG impacts. This should be done by conducting further collection and analysis of primary data, for example regarding raw material acquisition and fabric processing, so that companies can understand the detailed activities with the greatest GHG emissions and opportunities for reducing them.

Life cycle carbon emissions data will be most useful if done in a standard fashion, so that various LCAs can be more directly compared. This can be done in part by adhering to common standards such as PAS 2050. Several industries are also developing common sector guidance for measuring carbon emissions, including the beverage industry through the Beverage Industry Environmental Roundtable, the Outdoor Industry Association, and the Electronics Industry Citizenship Coalition.

Appendix A: Expert Interviews

The project team conducted three expert interviews seeking both opinions on the articles and findings from our literature review and guidance on the leading works in the field, as well as quantitative sources. The experts generally agreed that a well-developed framework for textiles has not yet been widely accepted. They had differing viewpoints on the quality of databases. Dr. Overcash, for example, resoundingly rejects just about all the databases in existence, preferring to conduct each analysis on its own, supplementing it with his own findings. On the contrary, Dr. Jolliet believes in the validity of Ecometrix (though he once was on their board). Contact details and brief notes on the experts follow.

- Greg Keoleian, Associate Professor and Co-Director, Center for Sustainable Systems, School of Natural Resources, University of Michigan
  Phone: 734-764-3194; E-mail: gregak@umich.edu

Keoleian is recognized as a leader in the LCA field. He is the president-elect of the International Society for Industrial Ecology. In our conversation he pointed us to several databases but did not place great confidence in any particular study or framework. He refered us to Michael Overcash and Olivier Jolliet as the only other true experts in this field.

- Michael Overcash, Professor of Chemical Engineering, North Carolina State University
  Phone: 919-571-8989; E-mail: mrovercash@ncstate.edu

Overcash is of the view that very little rigorous work has been published to date on textiles broadly and has little faith in the databases available. There are some valuable resources on both chemicals and the life cycle of laundry but little outside those areas. His institute does conduct LCA analysis and generally captures data for each product. He noted that Ann Arbor-based NSF International (http://www.nsf.org/) will likely be releasing a set of standards soon on textile LCA, building on their work in carpets.

- Olivier Jolliet, Associate Professor of Environmental Health Sciences, University of Michigan School of Public Health
  Olivier Jolliet Office: 734-647-0394; E-mail: ojolliet@umich.edu

Jolliet generally agrees that little has been published of note, and that there is especially a lack of literature that would enable comparisons across textile types. His focus is more on the chemicals and their impact. The Usetox database of chemical properties is also a valid source in his estimation.

Appendix B: Data Sources and Calculations

Chart 1 (Life Cycle Clothing GHG Emissions): Industry source, unpublished

Chart 2a&b (Comparative Energy Use and GHG Emissions from Fiber Production):

- Cotton, viscose, polyester, acrylic: 1997 Danish Environmental Protection Agency Environmental Report Number 369: Environmental Assessment of Textiles (referenced as "DEPA" below), page 174
- Wool raw material production estimated as 20 MJ/kg (from DEPA, 100% allocation to wool) + scouring energy estimated at 21.62 MJ/kg from New Zealand Merino Wool study, http://www.merinoinc.co.nz/Reports/LCA_NZ_Merino_Wool.pdf
- Wool methane estimate derived as follows:
    - Methane estimated at 11.6 kg/head/year per from NZ Ministry for the Environment (http://www.mfe.govt.nz/publications/climate/projected-balance-units-may05/html/page10.html) (although emissions estimates vary considerably: from 5.0 kg/head/year [Harinder P.S. Makkar et al., "Measuring Methane Production from Ruminants" page 111] to 19 kg/head/year [http://nzsm.webcentre.co.nz/article448.htm]).
    - One kg methane is equivalent to 23 kg CO_2 (IPCC 2001)
    - Average fleece weight may be 4.3 kg/yr (http://www2.dpi.qld.gov.au/sheep/7925.html#wool)
    - Calculation: 11.6 kg methane/yr * 23 / 4.3kg wool/yr = **62 kg CO_2e/kg wool**
    - Energy: coal-fired electricity generates 0.268 kg CO_2e/MJ, natural gas generates 0.158 kg CO_2e/MJ (derived from US EIA, http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html)
    - Wool CO_2e equivalent to fuel: 62 kg CO_2e / 0.268 kg CO_2e/MJ = **231 MJ / kg wool**
- Linen information derived from Masters of Linen study http://www.mastersoflinen.com/news/pdf/1209115075.pdf as follows:
    - Study states that 253g linen shirt used 100 times yields primary energy consumption of 6.0 MJ (and generates 130g CO2) per wearing, which equals 600 MJ (1,300g CO2) over its lifetime, or approximately 2400 MJ (5,200g CO2) per kg.
    - Study states that fiber cultivation generates 1% of primary energy consumption. 1%*2400 MJ/kg = 24 MJ/kg from fiber cultivation.
- Nylon data from PlasticsEurope Eco-profile for Nylon 66, http://lca.plasticseurope.org/download/n66.zip. Alternate estimates:
    - 160 MJ/kg in polyamide fiber production - http://www.ifm.eng.cam.ac.uk/sustainability/projects/mass/UK_textiles.pdf
    - 150 MJ/kg from 1995 APME LCA, referenced at http://www.cpm.chalmers.se/CPMDatabase/Scripts/sheet.asp?ActId=unknown01-20010917-81#Flow%20Data

Chart 3 (Use Phase Care Options):

- Ironing information derived from data in Continental Clothing LCA http://www.continentalclothing.com/?module=cms&P=382

- Dry cleaning information derived from: electricity use of 26.6 kWh/100 lbs clothing for perchloroethylene dry cleaning ("Comparison of Electricity and Natural Gas Use of Five Garment Care Technologies, ET 05.01", 2008, p2), and US average GHGs are 0.59 kg CO_2e/kWh from http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html
- Washer/Dryer information derived from:
  - The Federal Trade Commission – Appliance Energy Data: http://www.ftc.gov/bcp/conline/edcams/eande/appliances/clwasher.htm
  - Bole, Richard. "Life-Cycle Optimization of Residential Clothes Washer Replacement", Center for Sustainable Systems, University of Michigan, April 21, 2006. Available at: http://css.snre.umich.edu/css_doc/CSS06-03.pdf (Appendix C of the University of Michigan report contains detailed washer energy efficiency data, from the Association of Home Appliance Manufacturers)
  - Industry data (unpublished)

Chart 4 (Cotton T-Shirt 1): Data from Steinberger, Friot, Jolliet & Erkman. "A Spatially-explicit Life Cycle Inventory of the Global Textile Chain," *The International Journal of Life Cycle Assessment*, Springer Berlin/Heidelberg, May 2009.

Chart 5 (Cotton T-Shirt 2): data from Continental Clothing, http://www.continentalclothing.com/?module=cms&P=382

Chart 6 (Denim Jeans): Levi Strauss & Co.

Chart 7 (linen shirt): Masters of Linen LCA, http://www.mastersoflinen.com/news/pdf/1209115075.pdf

Chart 8 (viscose dress): Data from forthcoming LCA produced by industry source

Chart 9 (polyester blouse): Franklin Associates in 1993 LCA for the American Fiber Manufacturers' Association: http://www.fibersource.com/f-tutor/lca-page.htm

Other statistics:
Nylon: data from "Well Dressed," http://www.ifm.eng.cam.ac.uk/sustainability/projects/mass/UK_textiles.pdf
Acrylic: 1997 Danish Environmental Protection Agency Report Number 369 (DEPA)