dyson

Testimony
of
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Before the
Committee on Business and Labor
House of Representatives

Hearing on SB 488 A

May 27, 2015

Chairman Holvey, Vice Chairman Barton, and Members of the Committee,

I appreciate the opportunity to provide testimony on Senate Bill 488 A. Although Dyson deeply respects and understands the problem that the author is trying to solve with this bill, Dyson respectfully opposes SB 488 A as it is currently written. This legislation lacks a uniform test procedure preventing the equitable comparison between differing products noise levels and air speeds creating a competitive advantage to less environmentally friendly alternatives. My testimony below will address these concerns in more detail.

Lack of Uniform Test Procedure
Setting a level for sound (in decibels) without a uniform test procedure will create a meaningless requirement that would be used to compare the noise of one product over another because each product could be tested under differing testing protocols. For example, one product could be tested with the a sound meter 2 inches from the product running at maximum levels in a small room with no sound damping to reduce echoing. Another product could be tested with the sound meter 20 feet away from the product running intermittently over the course of one hour to approximate its actual usage in a restroom and in a large sound damping test chamber. One product could report a lower decibel rating but actually be louder.

For these reasons, energy standards, for example, all require detailed and complex test procedure to ensure uniform testing and reporting by all competitors and to prevent circumvention of the test procedure through possible loopholes. There is a real world example of this occurring. Mexico mandated energy labels for all products but had no defined test procedures. As a result, a consumer could see a label on a blender that was tested with sand in it and another blender that was tested with water in it and come to the conclusion that the one tested with water used less energy, but it may not, and the consumer would not know because all they would have to compare is the final reported energy rating.

Another example of this is snowmobiles. In National Parks, snowmobiles are required to meet noise emission standards. As part of this process, the National Park Service (NPS) tests and certifies snowmobiles in the field for compliance with the noise emissions standards. The NPS closely follows the standard procedure outlined by the Society for Aircraft Engineers (SAE J1161). SAE states that even under their test procedure sound pressure measurements have been known to vary as much as 6 to 10 dBA due to atmospheric, surface condition and vehicle fluctuation.

Further, a sound meter is purely a measurement of sound pressure measured in decibels. There are many different types of sound meters and many types of measurements can be taken, including absolute peak values or maximum sound pressure. People also have differing perceptions of sound or noise. Some music, for example, is noise to one person and pleasant music to another. Sound quality is an important factor, how irritating the sound is will not be covered by the type of measurement proposed.

Dyson and other companies do provide a decibel rating on hand dryers, but these are used to compare Dyson products against Dyson products, not to compare Dyson products against the products of other companies. Dyson’s own method was developed to replicate a person using the machine; however, other manufacturers may not include hands in or may include sound power measurements which are a measure of the sound transmitted rather than actually received.

Regarding the air speed requirement in the legislation, there are no international standards for measurement of airflow on the exit of hand dryers. Current measurements come from computation fluid dynamics modelling and the velocity again may not be the velocity acting on the user. Given all the differences in orifice size and the balances between flow and velocity it seems an arbitrary method. Based on a certain calculation methodology, Dyson Airblades have air speeds up to 450mph.

Advantage to Less Environmentally Friendly Alternatives

SB 488 A would thrust a legal requirement on hand dryers where none would exist for competing methods of drying hands. The point is that all hand drying products – not just ones using air -- should be compared. Although there is no label requirement, in a very competitive market, any advantage is exploited. This would be an unfair new law for an option that is more environmentally friendly. MIT's Material Systems Laboratory studied the question of the environmental implications of the hand dryer versus paper towel (see Appendix A). The main methods of drying hands in public places are high-speed hands-in dryers represented by the Dyson Airblade™ hand dryer, an Excel XLERATOR hand dryer, a standard warm air dryer, cotton roll towels, and paper towels (see Figure 1 below for examples).

Figure 1 Drying systems included in this study (left to right): Dyson Airblade™ hand dryer with a plastic cover, Excel XLERATOR® hand dryer, generic standard warm air hand dryer, generic cotton roll towels and dispenser, and paper towels and dispenser. Note: pictures are not shown with a consistent relative scale.

The study found that the environmental impact of high-speed hand dryers is generally lower than that of other hand-drying systems. The Global Warming Potential (GWP) of this drying system is nearly always the lowest. Paper towel system impact, by contrast, is driven by the production stage and cotton roll towel system impact by both the production and use stages. See Figure 1 below for additional detail on this.

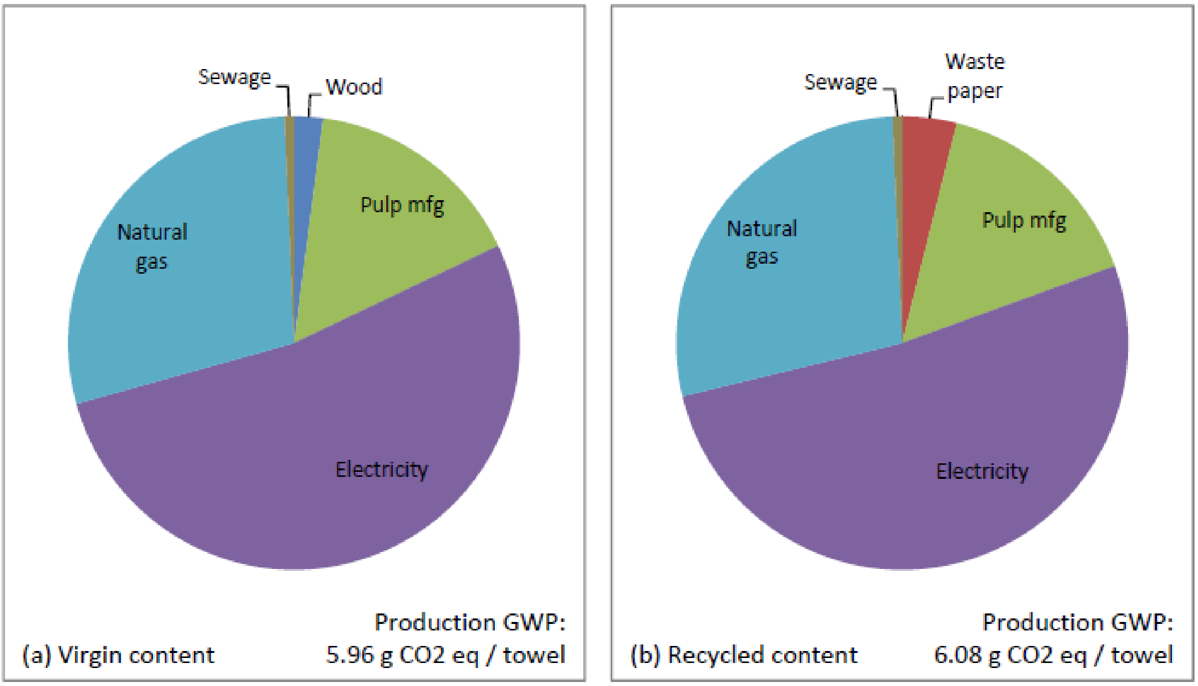

Figure 18 GWP breakdown of paper towel production from (a) virgin and (b) recycled content.

Air Speed
In regards to health, embolisms are only an issue when using high pressure airlines which could be operating at 5 bar of pressure above ambient. This is significantly above the pressure created by any hand dryer. Under hand drying circumstances, the user's skin would never see anything in excess of 0.4 bar above ambient.

Hygiene of Drying Hands
High speed hand dryers improve hygiene. These types of hand dryers actually work effectively to dry hands in 15 seconds, compared to older technology which relies on evaporation and takes twice as long to dry hands (30 seconds). Often users are not willing to wait a long time for hand drying. Further, damp hands can spread up to 1,000 times more bacteria than dry hands so driving people back towards the slower (possibly quieter) drying dryers could also cause hygiene issues.

Conclusion
Dyson is willing to work cooperatively to address how better to accomplish the objectives of this bill. Unfortunately, in its current form, it will have negative unintended consequences for Dyson and hand dryers generally and not achieve more pleasant sounding, environmentally friendly hand dryers in public areas.

We would respectfully ask the Committee to refer this legislation to the Rules Committee without a recommendation to provide additional time for us to work with the author and this Committee on a possible solution.

Thank you for considering our views, and we are available to discuss this in more detail.

APPENDIX A

Life Cycle Assessment of Hand Drying Systems

September 19, 2011

Commissioned by
Dyson, Inc.

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Contents

1 Introduction

The question of the environmental implications of the hand dryer versus paper towel is faced by many people, as evidenced by its coverage in the media [1-5]. As such, there are a number of studies that target this particular question, including a streamlined life cycle assessment conducted for Airdri Ltd. and Bobrick Washroom Equipment that compares a standard warm air dryer to paper towels [6], a hand dryer-towel comparison produced by MyClimate and commissioned by Dyson in Switzerland [7], a comparison between cotton roll towels and paper towels commissioned by Vendor [8], and some calculations made by the Climate Conservancy for Salon [9]. More comprehensive life cycle assessments that comply with the ISO 14040 and 14044 life cycle assessment standards [10, 11] are also available. These include a study for the European Textile Services Association (ETSA) that also compares cotton roll towels to paper towels [12], another investigating multiple types of tissue products for Kimberly-Clark [13], and a third for Excel Dryer that compares its XLERATOR® hand dryer to a standard warm air dryer and paper towels [14]. Dyson has also conducted a life cycle assessment of its Dyson Airblade™ hand dryer in accordance with the PAS 2050 standard [15] in order to obtain a Carbon Reduction Label from the Carbon Trust [16].

Among all these studies, only the one by MyClimate [7] compares all types of drying systems—a high-speed hands-in dryer represented by the Dyson Airblade™ hand dryer, a standard warm air dryer, cotton roll towels, and paper towels (see Figure 1 for images of these different drying systems). It does not include the hands-under variant of high-speed dryers, however. By contrast, the report conducted for Excel Dryer [14] includes a high-speed hands-under dryer—the XLERATOR® hand dryer—but then does not consider a high-speed hands-in dryer or cotton roll towels. And because of the studies' differing functional units, assumptions, and data, life cycle assessment outcomes cannot be easily compared. Dyson commissioned this study as a means of addressing this gap. *The goal of this analysis is to evaluate and compare the various hand-drying systems—including both variants of high-speed hand dryers—from the different studies by placing the systems on a consistent basis.*

Life cycle assessment (LCA) [17, 18] is used to conduct this study. LCA is a comprehensive framework with a level of detail that requires a strict adherence to a consistent methodology. This methodology is articulated in the International Organization for Standardization's set of LCA standards that are part of its ISO 14000 environmental management series. A life cycle assessment that follows the LCA standards ISO 14040 and 14044 [10, 11] contains four main steps:

- *Goal and scope definition* articulates the objectives, functional unit under consideration, and regional and temporal boundaries of the assessment.
- *Inventory analysis* entails the quantification of energy, water, and material resource requirements, and emissions to air, land, and water for all unit processes within the life cycle.
- *Impact assessment* evaluates the human and ecological effects of the resource consumption and emissions to the environment associated with the life cycle.

- *Interpretation of results* includes an evaluation of the impact assessment results within the context of the limitations, uncertainty, and assumptions in the inventory data and scope.

A critical review by a panel of experts is also required for studies where the results are intended to support comparative assertions that will be disclosed to the public.

This study has been conducted in accordance with the requirements of the ISO standards 14040 and 14044, including the critical review. The content in this report is grouped into the same four areas outlined in the standards, followed by conclusions, a summary of the critical review, and appendices.

2 Goal and scope

2.1 Goals

The overall goal of this study is to compare the life cycle environmental impact of several hand-drying systems using a consistent basis. Specific goals are to:

1) Evaluate how hand-drying systems impact the environment under different manufacturing and use scenarios.
2) Identify impact drivers and ways to target those factors.
3) Inform product design decisions.

This study was commissioned by Dyson and it is expected that the results will be used to support comparative assertions that are disclosed to the public. The report has two audiences. The first audience is any interested party who wishes to understand the data, assumptions, and methodologies used to calculate life cycle environmental impact for the hand-drying systems. The second audience is the Dyson engineers who are interested in understanding the drivers of environmental impact for the hand-drying systems.

2.2 Scope

The seven systems for drying hands evaluated in this report include:

1) A Dyson Airblade™ hand dryer with an aluminum cover (a high-speed hands-in dryer)
2) A Dyson Airblade™ hand dryer with a plastic cover (a high-speed hands-in dryer)
3) An Excel XLERATOR® hand dryer (a high-speed hands-under dryer)
4) A generic standard warm air hand dryer (a hands-under dryer)
5) Generic cotton roll towels
6) Generic paper towels manufactured from virgin content
7) Generic paper towels manufactured from 100% recycled content

In addition to the dryers and towels, packaging is considered in all cases, as well as dispensers in the case of the towel systems and a waste bin and bin liners for the paper towel systems (Table 1).

Figure 1 Drying systems included in this study (left to right): Dyson Airblade™ hand dryer with a plastic cover, Excel XLERATOR® hand dryer, generic standard warm air hand dryer, generic cotton roll towels and dispenser, and paper towels and dispenser. Note: pictures are not shown with a consistent relative scale.

Table 1 Additional product life cycles included in hand dryer or towel systems.

Drying system	Packaging	Dispenser	Waste bin	Bin liners
Airblade™ dryer, aluminum	✓			
Airblade™ dryer, plastic	✓			
XLERATOR® dryer	✓			
Standard dryer	✓			
Cotton roll towels	✓	✓		
Paper towels, virgin	✓	✓	✓	✓
Paper towels, 100% recycled	✓	✓	✓	✓

2.2.1 Functional unit

A single pair of dry hands represents the functional unit. The corresponding reference flows therefore include the allocated fraction of a hand dryer or the number of cotton or paper towels associated with drying that pair of hands (Table 2). For the hand dryers, "dry" is defined by the NSF Protocol P335 [19], which sets forth a standard for dryer operation and hygiene, thereby providing a consistent basis for determining use times. Although hygiene is part of the protocol and is another purpose of the systems that is of interest to the scientific community (e.g. [20-24]), it is not considered in this analysis.

Since hand dryers clearly dry more than one pair of hands over their lifetime, their impact has to be allocated across all these pairs of hands. The same holds true for the cotton roll towels, towel dispensers, waste bin, bin liners, and packaging used by these products. Allocation is accomplished by assuming dryers have a 5-year life span (given the 5-year warranties on the high-speed dryers [25, 26]), over which they dry 350,000 pairs of hands [27]—equal to approximately 1,350 pairs of hands a week. Therefore, 1/350,000 or 2.86×10^{-6} of the impact of a dryer is allocated to the functional unit. The same assumptions are used for the towel dispensers, waste bin, and packaging. The effect of dryer lifetime usage on environmental impact is investigated in the sensitivity analysis.

Bin liners and cotton roll towels are also used for multiple pairs of dry hands but do not last the full 350,000 uses. Therefore they require their own allocation strategies. If five bin liners are consumed each week—one for each workday [6]—each liner will correspond to, on average, 270 pairs of dry hands. Consequently, 1/270 or 0.0037 bin liners are allocated to the functional unit. Although waste bins and bin liners can also be used for the disposal of other objects, their impacts are fully allocated to paper towels, which represents a worst-case scenario for the paper towels. Additionally, the presence of paper towels will increase the need to change the liners. Likewise, the fact that cotton towels can be laundered and reused an average of 103 times [12] before they are disposed has to be taken into account when calculating the fraction of a towel required to fulfill the functional unit. No allocation is necessary for paper towels.

Table 2 Corresponding drying system reference flow given a functional unit of drying one pair of hands.

Drying system	Reference flow
Hand dryers	2.86×10^{-6} dryer and packaging Electricity to dry one pair of hands
Cotton roll towels	9.71×10^{-3} cotton towel and packaging[a] 2.86×10^{-6} cotton towel dispenser Laundry to wash a towel
Paper towels	2 towels and packaging[b] 2.86×10^{-6} paper towel dispenser 2.86×10^{-6} waste bin 3.7×10^{-2} bin liner

(a) Assuming one cotton roll towel pull per dry
(b) Assuming two paper towels per dry.

2.2.2 System boundary

The analysis includes all life cycle stages, from cradle to grave, along with transportation between each stage. These stages and their corresponding locations are shown in Figure 2 for the hand dryer, cotton roll towel, and paper towel systems. The United States is the primary region of focus for the use of the products in this study, although scenarios involving several other regions throughout the world have been evaluated in the sensitivity analyses. In order to put the hand-drying systems on equal footing from a supply chain standpoint and to make the analysis strictly a comparison between the performance of the product systems rather than between specific supply chain scenarios, all systems, with the exception of paper towels, are assumed to be manufactured in China and used in the United States. China is a common location for the manufacturing of technology products; it is also a reasonable assumption for the manufacture of cotton roll towels (see [12]). Paper towels, on the other hand, are assumed to be both manufactured and used in the United States because this represents the industry standard for a product that is used in a location where the raw materials are plentiful at a competitive price and the production is not labor-intensive.

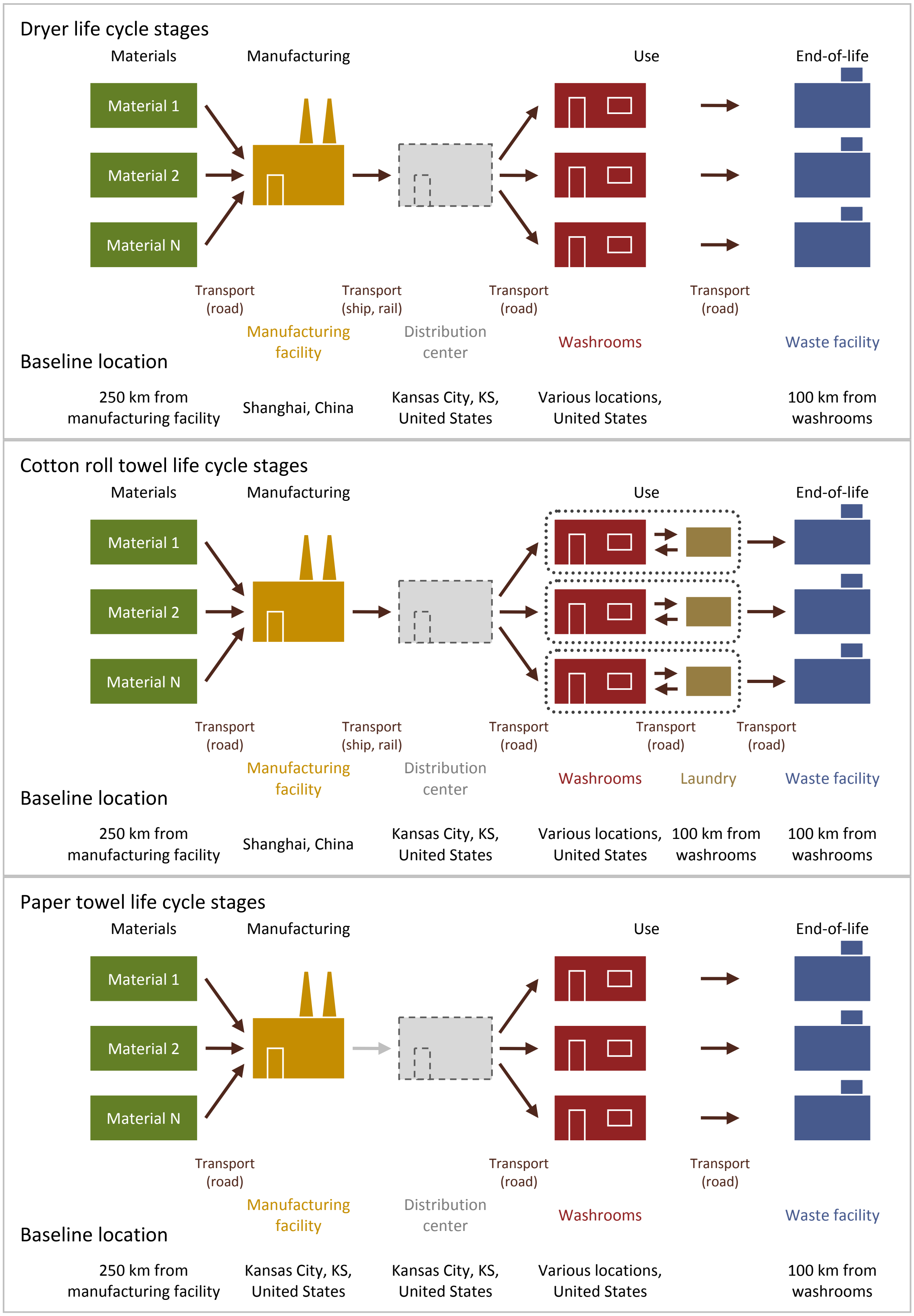

Figure 2 Hand dryer, cotton roll towel, and paper towel life cycle stages and corresponding locations assumptions for the baseline scenario.

2.2.2.1 Life cycle stages

Upstream processes such as the mining of ore or the extraction and refining of petroleum for vehicle fuel are included within system boundaries. Once the ore is extracted and refined into raw materials (the materials stage in Figure 2), the materials are transported to a manufacturing facility where they are processed and assembled into finished products (the manufacturing stage). Only the energy required to manufacture dryers or towels is accounted for in the calculation of manufacturing stage impact. Capital equipment (e.g. buildings, machines, etc.) used by Dyson or any of the other hand dryer or towel manufacturing firms is not included in the manufacturing phase of the analysis because the published reports on dryer and towel production that served as sources of inventory data for this report likewise do not include capital equipment in the primary production phase. This assumption is reasonable given the expected small contribution of auxiliary electricity and capital equipment to the overall life cycle burden of the hand-drying systems. Data for capital equipment upstream of drying system production, however, is included through use of the ecoinvent database for unit process inventory data.

After production, the dryers and cotton roll towels are transported from China to a distribution center in the US. The paper towel facility, by contrast, is located in the US and is therefore assumed to be co-located with a distribution center, which eliminates the need for a corresponding transportation step. Although transportation to and from the distribution center is accounted for, the impact due to the center itself is not included in the system because the burdens associated with operating warehouses are small in comparison with the burden of manufacturing. This is based on rough calculations using data from a case study by Carnegie Mellon University [28] that indicate that warehousing would be approximately 0.05% of the total GWP for dryers, 0.5 % for cotton roll towels, and 3% for paper towels (see Appendix A.7.1).

The products are next transported from the distribution center to a washroom, where the use stage takes place. For dryers, the use stage impact is solely due to the electricity required for operation. While the standard dryer, which heats the air, can potentially affect washroom HVAC performance, this effect is not considered in the analysis due to the difficulty of quantifying such an effect. Maintenance of the dryers is also assumed to be beyond the scope of this analysis because maintenance is typically a labor-driven activity, which is not included in the scope of environmental impact assessment. The use stage for the cotton roll towels encompasses not only the use of the towel inside a washroom, but also a cleaning step which takes place at a laundry facility. Consequently, cotton roll towels have an additional transportation step to deliver them to and from the laundry.

Finally, at the end-of-life, all product types are transported to a nearby waste facility where they are incinerated or sent to a landfill. With the exception of the cardboard packaging, there is no clear evidence that these products are commonly recycled—or in the case of cotton and paper towels, composted—in the US.

2.2.2.2 Allocation of recycled content

System boundaries also have to be defined when a product life cycle is part of an open loop recycling system, as is the case for the paper towels manufactured from recycled content. In such cases, allocation decisions for the raw material production, recycling, and end-of-life burdens are necessary because the paper towel system cannot be expanded to encompass all product life cycles due to lack of knowledge about the additional products. Various allocation strategies are described in Appendix A.4. The cut-off method, which assigns the burden of recycling to the product life cycles that use recycled content (Figure 36), is chosen for the baseline. Since paper towels can use recycled content but are rarely recycled themselves (same assumption as in the Kimberly-Clark study [13]), they represent the final product of an open loop recycling system and are allocated the burdens from recycling waste paper and end-of-life in accordance with the selected strategy.

2.2.3 Cut-off criteria

In addition to hand-drying system boundaries, the cut-off criteria, or the point at which input or output flows are excluded from the analysis, have to be defined for each system. These criteria can be based on the mass, energy, or environmental significance of the flows. In the case of the Dyson Airblade™ hand dryer, all parts are accounted for, with the smaller parts such as screws or fasteners aggregated into a single "part" [27]. The data on which this analysis is based also included a breakdown of the resistors and other components on the Dyson Airblade™ hand dryer's printed circuit board; this level of detail, however, was deemed unnecessary and the data re-aggregated to circuit board level.

The XLERATOR® dryer, standard dryer, and paper towel life cycle inventories were all based on the study for Excel Dryer [14]. This study included as many components as possible given available information, and predicted that omitted parts would account for less 1% of total impact. Lastly, the cotton roll towels were based on the ETSA study [12], which excluded processes that consisted of less than 1% of total mass and energy balance. The number of processes excluded, however, was limited so that they accounted for no more than 5% of the total balance.

3 Life cycle inventory analysis

This section details the data and assumptions used to conduct a life cycle inventory analysis for each hand-drying system. The complete inventory is generated by combining bill of activities[1] data for each system with life cycle inventory data of required unit processes from existing databases (Figure 3). Whenever possible, data used in this study were obtained from existing sources.

Bill of activities data sources and assumptions for all hand-drying systems are detailed by life cycle stage. Some of the assumptions are later evaluated in the sensitivity and uncertainty analyses to assess their effect on the LCA results and drying system comparison. The bill of activities data information is followed by a description of the life cycle inventory data used by the unit processes.

Table 3 summarizes the assumptions made for the baseline scenario; detailed data for each hand-drying system can be found in Appendix A.1. Much of the data for product compositions and manufacturing processes are derived from other LCA studies on the systems; when necessary, assumptions are made in order to insure that the analyses are conducted on a consistent basis (e.g., production or use location).

[1] "Bill of activities" is defined to include material composition, production requirements, use requirements, and transportation distances for a product system.

In particular, all products, with the exception of paper towels, are assumed to be manufactured in China (see Figure 2), even though this is not necessarily the case for the dryers in reality (e.g., the XLERATOR® dryer is produced in the US [14] and the Dyson Airblade™ hand dryer is produced in Malaysia [27]). The use of a consistent basis for manufacturing location and transportation distances is motivated by an objective of the study to compare the influence of different manufacturing and use scenarios of the different hand-drying systems. This is only meaningful if the supply chain scenarios are the same and plausible for similar products. China is a highly plausible location for the production of hand dryers because it is a common location for the manufacturing of technological products. Using a consistent basis enables a comparison among products that is focused on product attributes including material composition, manufacturing process, and energy consumption, and not on supply chain configuration (which is not known for all products). However, a sensitivity analysis on manufacturing location is included to explore the impact of this assumption. Paper towels are the exception to this practice: this study assumes that the paper towels are produced and used in the US because this is the industry standard for a product that is used in a location where the raw materials are plentiful at a competitive price and the production is not labor-intensive.

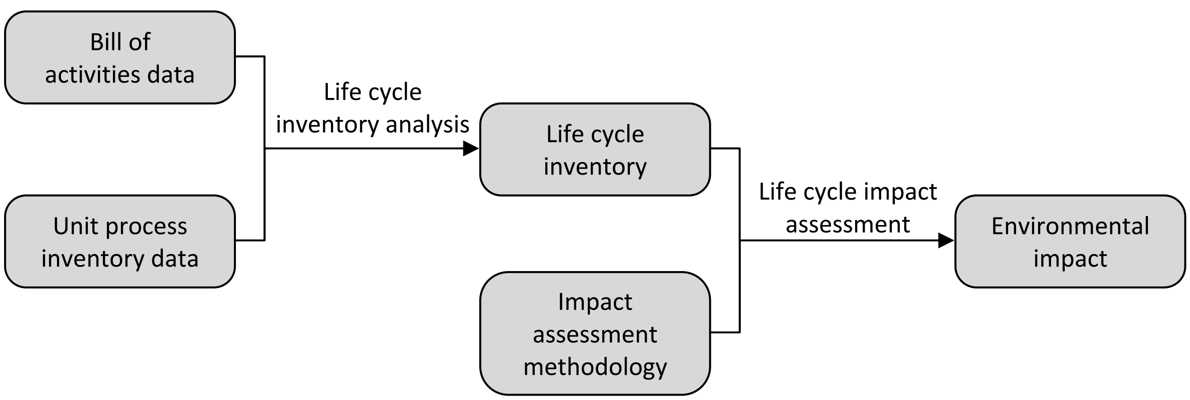

Figure 3 Steps to convert bill of activities data to environmental impact.

3.1 Bill of activities

The bills of activities for each product system are detailed in Appendix A.1. They are combined with unit process inventory data to construct drying system life cycle inventories. Most of these data were obtained from critically reviewed LCAs dating from 2006 and later. With the exception of the cotton roll towel bill of activities, data are at most 10 years old. Dyson supplied data for its Dyson Airblade™ hand dryers [27]. Data for the XLERATOR® and standard dryers were taken from the Excel study [14], which obtained its data directly from Excel Dryer, Inc and—in the case of the standard dryer—from the Airdri streamlined LCA [6]. Cotton roll towel data were obtained from the ETSA report [12]; this study used existing literature from the 1990s and 2000s for cotton roll towel production, but conducted its own survey of laundries to develop a laundering process inventory. Finally, paper towel data were based on a combination of the Excel [14], Kimberly-Clark [13], and ETSA [12] studies. The Excel study also relied on the Kimberly-Clark report for paper towel data, whereas the ETSA study relied on a 2001 report on the best available techniques report in the pulp and paper industry [29].

Table 3 Assumptions used to generate hand-drying system life cycle inventories for the baseline analysis.

Drying system	Airblade™ (high-speed hands-in dryer)	XLERATOR® (high-speed hands-under dryer)	Standard warm air dryer	Cotton roll towels	Paper towels
Functional unit	1 pair of dry hands				
Lifetime usage	350,000 pairs of dry hands over 5 years [26, 27]				
Mass (+ manufacturing scrap) per dryer or towel	Al: 14.8 kg (1.43 kg) Pl: 9.9 kg (2.16 kg) [27]	9.4 kg (1.12 kg) [14]	6.4 kg (0.9 kg) [14]	16.2 g (2.2 g) [12]	1.98 g (0.08 g) [14]
Manufacturing location	China	China	China	China	US
Manufacturing energy per dryer or towel	146 MJ electricity [27]	156 MJ electricity [14]	156 MJ electricity [14]	431 kJ electricity 507 kJ gas [12]	14.7 kJ electricity 24.4 kJ gas [14]
Use location	US				
Use intensity	12 sec @ 1,400 W + 0 sec @ 0 W + 439 sec @ 1 W	20 sec @ 1,500 W + 1.5 sec @ 750 W + 429 sec @ 1 W	31 sec @ 2,300 W + 1.5 sec @ 1,150 W + 406 sec @ 0.4 W	1 towel (pull) + laundry	2 towels
End-of-life scenario	76.7% of cardboard recycled 19% of remaining waste incinerated with energy recovery 81% of remaining waste landfilled with methane capture and conversion to electricity [30, 31]				
Transportation					
Raw material to plant	250 km via truck				
Plant to warehouse	10,500 km via ocean freighter + 2,600 km via freight train + 24 km via truck (excl. paper towels)				
Warehouse to washroom	1,760 km via truck				
Washroom to laundry and back	100 km via truck (cotton towels only)				
Washroom to waste facility	100 km via truck				
Additional lifecycles	Packaging	Packaging	Packaging	Packaging, dispenser	Packaging, dispenser, waste bin, bin liners
Packaging per dryer or towel	2.94 kg cardboard [27]	0.27 kg cardboard [14]	0.45 kg cardboard [14]	0.08 g polyethylene	0.18 g cardboard [14]

3.1.1 Production: materials and manufacturing

This analysis accounts for the impact of material production, including upstream impact starting from ore extraction. Dryer materials are conservatively assumed to be manufactured from virgin content. They are then transported 250 km from their respective production or storage facility to the manufacturing plant where dryer or towel manufacturing takes place. Two hundred fifty kilometers was chosen as an intermediate distance between the 750 km by road assumed in Airdri and Excel studies [6, 14], and the 30 km used in the report for Carbon Trust [27]. With the exception of the paper towel systems, all materials production and manufacturing takes place in China (see discussion at the beginning of Section 3 about the use of a consistent basis); consequently, the Chinese average grid mix, along with Chinese emission factors when available, is assumed for the production of electricity. Paper towels, by contrast, are assumed to be manufactured in the US and thus rely on the US grid (see discussion in Section 3). Once the products are finished, they are then shipped to a distribution center in the US and from there to a washroom. All transportation steps in this analysis are consolidated into a separate life cycle stage and summarized in Section 3.1.4.

Materials and manufacturing data for the aluminum and the plastic Dyson Airblade™ hand dryers were provided by Dyson and are based on the firm's analysis for its Carbon Reduction Label through the Carbon Trust [27]. Melamine is assumed for the bulk molding compound. Materials data for the dryers account for a 9.7% and a 22% scrap rate for the aluminum and plastic dryers, respectively, which represents the worst-case scenario for material loss. Capital equipment used in dryer manufacture is not included (in accordance with the system boundaries, detailed in Section 2.2.2.1).

Corresponding data for the XLERATOR®, the high-speed hands-under dryer, were based on the study prepared for Excel Dryer [14]. The Excel study uses a generic bill of activities that does not represent any one XLERATOR® in Excel Dryer's product line. Specifically, the report assumes that the XLERATOR®'s cover is a combination of the dryer's three available covers: stainless steel, plastic, and chrome finish. This assumption is carried over into this study because no alternative data were available for the individual covers. The same study is used to obtain production data for a standard warm air dryer (which is, in turn, based on the Airdri B-709 model from the Environmental Resources Management study conducted for Airdri Ltd. and Bobrick Washroom Equipment [6]). For both dryers, polypropylene is assumed for unknown plastic types, such as the "Plastic mixture" listed in the products' bills of materials for the housing retainer and motor plastics. The dryers also contain unspecified mass. This mass is accounted for when calculating transportation stage impact, but is assumed to have no influence on production stage impact. Finally, a 15% scrap rate—around the average rate of the two Dyson Airblade™ hand dryers—is added to the material input flows of both dryers in order to ensure an accurate comparison. Scrap values in Table 3, however, are slightly less than 15% because the scrap rate was not applied to electronic components or unspecified mass.

Production data for the cotton roll towels were obtained from the Okö-Institut report for the European Textile Services Association [12]. The production of these towels includes production of cotton fibers, spinning and sizing of the yarn, and weaving, de-sizing, and bleaching of the fabric. A 10% weight loss is assumed in the spinning process [12], plus a 2% loss in weaving [32]. Thus, it takes 18.4 grams of cotton fibers to produce the 16.2 grams of cotton towel that represent one pull of the roll [12]. The dispenser used for the cotton towels is based on the paper towel dispenser in the Excel study, although no batteries or circuitry associated with automatic paper towel dispensers are included since the towels are presumably pulled by hand from the roll.

Paper towels manufactured from 100% virgin and from 100% recycled content are examined in this analysis. The former is assumed to use pulp manufactured via the sulfate or kraft pulping process, the dominant pulping process that accounts for 80% of the world's pulp production [33], and bleached using elemental chlorine free (ECF) technology, the most common bleaching process for sulfate pulp in the US as of 2002 [34]. This pulp is then transported 250 km (a distance consistent with raw material transportation distances for the hand dryers) from its respective facility to a non-integrated manufacturing plant where the paper towels are produced. Virgin paper towel manufacturing data were based on the Excel Dryer [14], Kimberly-Clark [13], and ETSA [12] studies.

Paper towels manufactured from recycled content were also assumed to be produced in a non-integrated plant. In such cases, market deinked pulp would be transported to this plant from its respective manufacturing facility and used as a raw material in paper towel production. Bill of activities and inventory data for deinked pulp manufactured from 100% recycled content, however, were unavailable even among the critically reviewed LCA studies. The Kimberly-Clark [13] report provides an incomplete inventory, while the study by Excel [14] does not even account for the environmental impact from pulp manufacturing (this is acknowledged in the report). Although the ETSA [12] study provides an inventory for tissue manufacturing, this inventory is for an integrated plant (where pulp and tissue are manufactured in a continuous process) and assumes only 50% recycled content

Given the lack of available data, this study made simplifying assumptions for the deinked pulp manufacturing process. Specifically, the impact associated with manufacturing deinked pulp was assumed equal to that associated with manufacturing ECF-bleached sulfate pulp. Wood in the sulfate pulp process, however, was replaced with 1.5 kg of waste paper [12]. This substitution addresses key differences in raw material acquisition, but it may leave some processes in the pulping step that are required only for virgin material production (such as wood chipping). While these assumptions introduce uncertainty to the results (more so than the results of paper towels manufactured from virgin content), the uncertainty cannot be quantified due to lack of actual inventory data for paper towels. A more detailed study on recycled paper towels is recommended; since no such study currently exists, paper towel results from this study were compared with results from the other LCAs in Appendix A.6.3 to ensure this study's assumptions were reasonable

In both cases, pulp and tissue were manufactured in the same country where the use stage takes place (see discussion in Section 3). Additionally, this assumption is consistent with the Kimberly-Clark study. Paper towels have a final product mass of 1.98 g; a 3.85% manufacturing loss is accounted for in raw material requirements [13, 14]. The manufacturing plant is also assumed to be is co-located with a distribution center, thus eliminating the need for transportation between manufacturing plant and warehouse. This is a reasonable assumption because the impact of any transport between the plant and the distribution center would be miniscule in comparison with the impact of transporting the hand dryers and cotton roll towels over 13,000-km from China to their respective distribution centers.

The results for the paper towels containing recycled content are presented using the cut-off allocation approach, which is detailed in Appendix A.4. This allocation scheme was selected for the baseline analysis because it only accounts for the burdens directly associated with the production and disposal of the recycled-content towels. Paper towels are not recycled (same assumption as the Kimberly-Clark study [13]) and therefore represent the final product life cycle in an open loop recycling system. Thus, following the cut-off allocation scheme, paper towels manufactured from 100% recycled content are assigned the full burden from recycling waste paper back into pulp, and the full burden from end-of-life.

In addition to the towel life cycle, life cycles for a dispenser, waste bin, and bin liners are included in the assessment of paper towel hand-drying systems. The dispenser is the same as that used for the cotton towels; the waste bin is assumed to be entirely composed of steel, and the bin liners from polyethylene.

3.1.2 Use

Ideally, bill of activities data for the use phase would include details of washroom visitor usage patterns for each hand-drying system—how long they spent operating each dryer or how many towels they used after washing hands. Such data would also cover the significant variation in the way people dry their hands due to differences in hand sizes, in preferences about acceptable dryness, and in willingness to spend time drying hands. However, the reality is that there are no existing data sources capturing this wide variation, nor is there a common method for determining hand dryness across all the different drying systems. While this study has not attempted to address this gap, the authors have nonetheless made every effort to characterize drying system use intensity using the best available data and a consistent basis for comparison.

Use intensity represents the amount of resources each hand-drying system requires to dry a pair of hands. For hand dryers, this is related to the time users spend operating the dryers. Hand dryer dry times have been incorporated into the study in two ways: (1) measured according to a standard that defines when hands are dry and (2) reported by dryer manufacturers (Table 4). To ensure a consistent, scientific basis when comparing hand dryers, this study adopts measured dry times as its primary baseline. These times were measured according to the NSF Protocol P335 [19] (see Appendix A.5), which defines hygienically dry hands has having less than 0.1 grams of moisture remaining after drying. NSF protocol measurements were performed by Dyson. Manufacturer-reported dry times are used as a secondary baseline for some analyses in Section 4.1. These reported dry times were obtained from dryer specifications taken from manufacturers' websites. Neither Excel Dryer nor the standard dryer manufacturers, however, provide documentation on how they arrived at their dryers' respective dry times or what their basis was for dryness.

Variation in use intensity is also evaluated in order to assess the consequences of differing user preferences and thus, differing usage patterns. For instance, users may prefer to hold their hands in the air stream until a desired dryness is achieved—referred to as *drying-driven usage* in this report. The dry times for drying-driven usage are defined as 50% below to 25% above the measured baseline dry times (as defined by the NSF Protocol P335). Alternatively, users may prefer to wait the same length of time for their hands to dry, regardless of dryer type, before leaving—referred to as *time-driven usage*.

Drying-driven usage is assessed in a sensitivity analysis (see Section 5.1.4) and both drying- and time-driven usage patterns are assessed in the uncertainty analysis (see Section 0).

Table 4 Measured and reported dry times for hand dryers.

Dryer	Measured NSF P335 for US	Reported
Airblade™	12 sec [27]	12 sec [35]
XLERATOR®	20 sec [27]	12 sec [14]
Standard dryer	31 sec [27]	30 sec [6]

Once dry time is determined, it is then multiplied by the dryer's in-use rated power to arrive at the energy consumed during operation. In-use energy consumption, though, is only part of a dryer's total energy requirement as dryers also consume energy even when not actively drying hands. In addition to dry time, both the XLERATOR® and the standard dryers are assumed to have a 1.5-second spin-down time at half power [14]; the Dyson Airblade™ hand dryer, by contrast, uses a digital motor and does not consume power during spin-down [27]. All dryers are also assumed to have sensors that require energy when in standby mode. The XLERATOR® is assumed to have the same 1-W standby power consumption as the Dyson Airblade™ hand dryer [35], whereas the standard dryer is lower at 0.4-W [36]. Time spent on standby is calculated by subtracting the total use and spin-down time for 350,000 pairs of hands from the total time in the 5-year dryer life span. This total standby time is then normalized by the 350,000 uses and multiplied by standby power rating. From here, spin-down and standby energy consumptions are added to a dryer's in-use energy consumption to arrive at the total energy allocated to drying a pair of hands. The US average electric grid mix is used when assessing the environmental impact of this energy. Table 5 summarizes dryer power consumption, along with spin-down and standby times; additional details for calculating dryer energy consumption can be found in Appendix A.1.1.

Table 5 Dryer power consumption during use, spin-down, and standby.

	In-use	Spin-down		Standby	
	Power	Time	Power	Power	Time
Airblade™	1,400 W [35]	0 sec	0 W [27]	1 W [35]	439 sec
XLERATOR®	1,500 W [25]	1.5 sec [14]	750 W [14]	1 W	429 sec
Standard dryer	2,300 W [27]	1.5 sec [14]	1,150 W	0.4 W [36]	418 sec

The use intensity of the cotton roll towel drying system is represented by one pull on a cotton towel roll per functional unit, equal to the ETSA study's assumption [12]. While the in-washroom use of cotton roll towels does not have an impact, laundering the towels does. The laundering process is also based on the ETSA study [12]. Used towels are transported 50 km from the washroom to the laundry, where they are washed and thermally disinfected before being packaged in plastic film and returned to the washroom.

Unlike the hand dryers, there is no equivalent protocol for determining the number of paper towels required to achieve a specific level of dryness. Thus, the paper towel baseline assumes a use intensity of two towels per functional unit based on observational data from a University of Florida study [37]. As part of the UF study, researchers observed the length of time public washroom users washed their hands and the number of paper towels they took to dry their hands. Paper towel usage varied between one and seven towels, with an average of 2.1 towels per user. It should be noted that the two-paper towel use intensity assumption is consistent with several other LCA studies (see Table 40), a noteworthy exception being the Kimberly-Clark Study, which assumes 1.5 paper towels. However, none of the studies provides any rigorous justification for the number of paper towels used, including Kimberly-Clark. Thus, the data from the UF study is used as the basis for the number of paper towels in this study. Another consideration is that the exact number of paper towels will likely depend on towel mass, which varies among the different studies surveyed. Both use intensity and towel mass are later explored in a sensitivity analysis (see Sections 5.1.4 and 5.1.9). Since paper towels, packaging, dispensers, the waste bin, and bin liners do not require any energy during use, they therefore have to impact in this stage.

3.1.3 End-of-life

Once the hand dryers or towels are no longer in use, the products are transported 100 km to a waste facility, consistent with [27], and disposed according to US average waste and recycling fractions from 2008 [30]. Thus, 76.7% of cardboard packaging is recovered for recycling; each kilogram of cardboard is assumed to displace 0.78 kg of new cardboard (estimated based on [12]). Nineteen percent of the remaining cardboard and all other waste is incinerated, with the remaining 81% sent to the landfill.

Both energy recovery from incineration and methane capture from landfill emissions are considered in the baseline scenario. Incineration energy recovery is assumed to produce 0.65 kWh of electricity per kilogram of waste incinerated [38]. Since this 0.65-kWh represents the avoided production of electricity, each drying system is credited with 0.632 g CO_2 eq per kilogram of waste incinerated—the emissions associated with producing 0.65 kWh of electricity given the US average grid mix. Methane captured from landfill emissions is also assumed to be burned with energy recovery to produce electricity. Additional details and references for this process can be found in Appendix A.2

Aside from the recycling of cardboard packaging, no other recycling is assumed to take place. While hand dryers can be recycled (and indeed are required to be recycled in Europe per the waste electrical and electronic equipment directive [39]), there is no clear evidence that this is common practice in the US. Paper towel recycling is also possible as noted by Kimberly-Clark [40], although their LCA study [13] assumes that the paper towels are not recovered after disposal. Like the hand dryers, there is no strong evidence that recycling paper towels is common practice in the US; composting, however, is gaining ground (e.g. [41, 42]) and is thus addressed in the sensitivity analysis (see Section 5.1.5). Cotton towels are not recycled, but can potentially be reused as industrial cleaning cloths [12] (although this scenario is not considered in this analysis).

3.1.4 Transportation

Transportation takes place between each of the life cycle stages. Distances are either taken from literature, or estimated according to production, use, and end-of-life locations. Table 6 lists the distance and vehicle type for each transportation step. Vehicle types are chosen to match as closely as possible to those used in [12, 27]. Some steps are not included in the paper towel life cycle because the towels are assumed to be manufactured in the same country where they are used and have a manufacturing facility co-located with their warehouse. Cotton roll towels have the additional step of being transported to and from the laundry.

Table 6 Transportation vehicles and distances for all products (unless noted otherwise).

What	To where	Distance	Vehicle	Notes
Raw materials	Manufacturing plant	250 km	>16t truck	
Finished product	Long Beach port	10,500 km [43]	Ocean freighter	Excluding paper towels
Finished product	Warehouse	2,600 km 24 km[a]	Freight train >32t truck	Excluding paper towels
Finished product	Washroom	1,760 km[b]	>32t truck	
Dirty / clean towels	Laundry & back	100 km [12]	3.5-7.5t truck	Cotton towels only
Used product	Waste facility	100 km [27]	7.5-16t truck	

(a) Estimated using [27, 44]

(b) Estimated by averaging driving distances from Kansas City, KS to New York, NY; Los Angeles, CA; and Chicago, IL using [44].

3.1.5 Data quality: sensitivity analysis

Numerous assumptions are made in the definition of bills of activities. A sensitivity analysis is used to explore the extent to which variability in the baseline scenario assumptions (detailed in Sections 3.1.1 through 3.1.4) affects the environmental impacts of the hand-drying systems. The results of the sensitivity analysis are presented in Section 5.1. The analysis evaluates a range of scenarios that deviate from the baseline. The baseline assumptions addressed include (with baseline values shown in parentheses):

- Lifetime usage (350,000) – number of pairs of hands dried over the 5-year product life span.
- Manufacturing phase electric grid mix (China or US average mix) – technology portfolio that supplies electric power for dryer and towel production.
- Use phase electric grid mix (US average mix) – technology portfolio that supplies electric power for dryer and towel use.

- Use intensity (varies by product) – length of dry time for dryers, or number of paper towels or cotton roll towel pulls required to dry hands.

- End-of-life scenario (19% incinerated, 81% landfilled with energy recovery) – fraction of waste incinerated, landfilled, recycled, or composted; energy recovery assumption is maintained throughout .

- Dryer electronics unit process (Electronic component, active, unspecified) – unit process inventory chosen to represent the control and optics assemblies in the XLERATOR® and standard dryers.

- Cotton roll towel reuses (103 cycles) – number of times cotton roll towels can be laundered and reused before disposal.

- Paper towel mass (1.98 g) – mass of virgin- and recycled-content paper towels.

- Pulp manufacturing process (ECF-bleached sulfate) – manufacturing process of pulp used by virgin paper towels.

- End-of-life allocation methodology for recycled content in paper towels (cut-off) – allocation of the burden of primary material production, recycling, and end-of-life processes.

- Manufacturing location (China or US) – where the products are manufactured; affects production electric grid mix and transportation distances.

- Use location (US) – where the products are used; affects transportation distances, electric grid mix, and end-of-life scenario.

3.2 Unit process inventory data

In addition to the bill of activities data, unit process inventory data are also necessary to generate a life cycle inventory. A unit process is the smallest element considered in the life cycle inventory analysis for which input and output data are quantified [11]. The inputs and outputs can be in terms of other unit processes (e.g., electricity or steel production) or basic substances (e.g., minerals or gaseous emissions). These unit inventories are typically obtained from databases such as ecoinvent [32] and USLCI [45].

Whenever possible, the unit process inventory data for the life cycle inventories are taken from the ecoinvent Database v2.1 [32]. The majority of ecoinvent unit processes are used without modification. Consequently, they represent the database's default assumptions such as the inclusion of capital equipment for raw materials production, a mixture of country-specific emissions factors for a single country's electricity production owing to data availability limitations, and the use of European fuels and emissions factors for road transportation. In a few cases, though, ecoinvent process data is modified or data is adopted from external sources because of a lack of existing inventory data:

- Galvanized steel – created using ecoinvent data for steel and zinc coating

- Sheet steel sheet – created using ecoinvent data for steel and rolling
- Plastic mixture with extrusion – created using ecoinvent data for polypropylene and extrusion
- Glass fiber reinforced polypropylene – created using ecoinvent data for glass fibers and polypropylene
- Polycarbonate / acrylonitrile-butadiene-styrene – mixture of the two polymers, based on [27]
- Cotton roll towel manufacturing – adopted from the ETSA study [12]; these processes include spinning the cotton fibers into yarn, sizing the yarn, weaving the towels, and de-sizing, scouring, and bleaching
- Cotton towel laundering – adopted from the ETSA study, which lists the detergent, energy, and water required to wash the towels
- Pulp from waste paper – a modified ecoinvent sulfate pulping process (ECF-bleached) in which wood is replaced with 1.5 kg waste paper (based on [12])
- Cardboard recycling – created using ecoinvent data with an estimated recycling rate from [12]
- Incineration with energy recovery – based on ecoinvent data with an estimated electricity generation rate from [38]
- Landfill with methane capture – based on ecoinvent data with estimated methane capture and electricity generation rates from [46]
- Composting – based on data from a European Commission study on biodegradable MSW [47]

Bills of activities for these modified unit processes are included in Appendix A.2. Also, a generic ecoinvent unit process, "Electronic component, active, unspecified," the same unit process as in the Excel study [14], is used for the XLERATOR and standard dryer electronic components because specific information is not available for these components.

3.3 Uncertainty analyses

Uncertainty analyses are used to assess the consequences of variability or uncertainty in the inputs on environmental impact results of the hand drying systems. Two types of uncertainty analyses are conducted in this study. The first addresses variability in the baseline scenario assumptions. Distributions are assigned to parameters such as lifetime usage, electric grid mix, and use intensity. A Monte Carlo simulation is then employed to generate scenarios given the parameter distributions and calculate the resulting environmental impact distribution.

The second analysis investigates uncertainty and variability in the bill of activities data. In comparison to the first analysis, which addresses scenario-level variables (e.g. use intensity), this analysis focuses on the quantity of each unit process required by a hand-drying system. This quantity is related to, but not the same as, the scenario-level variables: for instance, the bill of activities data include hand dryer use phase electricity consumption, which not only depends on use intensity, but also on the dryer's power rating. Often, however, uncertainty data is not available or cannot be derived for the unit process quantities included in the bill of activities.

A pedigree matrix approach [32] is therefore employed to translate qualitative assessments of the data sources into quantifiable uncertainty calculations. As part of this method, the bill of activities data sources are first evaluated based on six characteristics: reliability, completeness, temporal correlation, geographic correlation, further technological correlation, and sample size. One of five quality levels that describe the degree of uncertainty is chosen for each of the characteristics based on descriptions found in [32]. These quality levels are, in turn, each associated with an uncertainty factor that quantifies their uncertainty (Table 7). Lower quality level values represent higher confidence in the data and thus translate to smaller uncertainty factors. A seventh "basic uncertainty factor" is also added according to whether the process represents an input or output to the technosphere or emissions. Finally, uncertainty factors are used to calculate the geometric standard deviation (SD_g) of the bill of activities data using the following equation:

$$SD_g = e^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_7)]^2}}$$

U_x represent the uncertainty factors of the six characteristics plus the basic uncertainty factor.

The pedigree matrix approach is applied to each element in the bill of activities and the resulting geometric standard deviations entered into SimaPro, where they are used to scale the distribution means (represented by the baseline unit process quantities). A Monte Carlo simulation is then run to assess the consequences of data source quality on environmental impact. The results are presented in Section 5.2.2 and quality levels assigned to each process are listed in Appendix A.3.

Table 7 Pedigree matrix uncertainty factors [32].

Quality Level	1	2	3	4	5
Reliability	1.00	1.05	1.10	1.20	1.50
Completeness	1.00	1.02	1.05	1.10	1.20
Temporal correlation	1.00	1.03	1.10	1.20	1.50
Geographical correlation	1.00	1.01	1.02	—	1.10
Further technological correlation	1.00	—	1.20	1.50	2.00
Sample size	1.00	1.02	1.05	1.10	1.20

4 Life cycle impact assessment

4.1 Life cycle impact assessment methodologies

The environmental impacts associated with a life cycle inventory can be calculated using a life cycle impact assessment (LCIA) methodology. LCIA calculations in this study have been performed using the

SimaPro 7 software package for the global warming potential (GWP), IMPACT 2002+, and cumulative energy demand (CED) methodologies. Results are also presented for water use (an elementary flow) and land occupation (a midpoint category in the IMPACT 2002+ methodology). No value choices or weighting are used in the application of these impact assessment methodologies. Each methodology is described below along with a justification for its use.

4.1.1 Global warming potential

Global warming potential (GWP) [48] incorporates the impact of gaseous emissions according to their potential to contribute to global warming based on the values published in 2007 by the Intergovernmental Panel on Climate Change (IPCC). The impacts for all gaseous emissions are evaluated relative to carbon dioxide using characterization factors that translate the mass of each gas into an equivalent mass of carbon dioxide (e.g. 1 kg CH_4 emitted into the atmosphere is equivalent to 25 kg CO_2 [49]). These factors are internationally accepted as a means of characterizing greenhouse gas emissions. Resource consumption and liquid and solid emissions are not included in the GWP methodology because they do not directly contribute to global warming. Biogenic carbon dioxide and carbon monoxide flows are also not included in the accounting (unless the analysis involves carbon sequestration); biogenic methane, however, is included[2]. In this report, characterization factors are based on a 100-year time frame because they are the most commonly used factors in LCA studies.

GWP was selected as an LCIA metric because of its high profile in the assessment of product environmental performance for numerous product types across the world and particularly for energy-intensive products. Furthermore, the metric is used in virtually all of the studies used as references for this study. For these reasons GWP is used as the primary means for comparison of environmental impact.

4.1.2 IMPACT 2002+

IMPACT 2002+ [50] is a damage-oriented method that evaluates environmental impact in four endpoint categories: human health, ecosystem quality, climate change, and resources. These categories are calculated from 15 midpoint categories (shown in Figure 4) which, in turn, have been adapted from IMPACT 2002, Eco-indicator 99, CML (Center of Environmental Science), and IPCC. Damage to Human Health is in units of disability adjusted life years (DALY), implying that different disabilities caused by diseases are weighted. Ecosystem Quality is reported in units of potentially disappeared fraction of plant species ($PDF \cdot m^2 \cdot yr$). Climate Change is similar to GWP from above, but uses characterization factors based on a 500-year time frame. Finally, Resources includes assessment of minerals and fossil fuels in units of MJ. Each damage category can then be normalized by average European impacts and weighted in order to aggregate all impacts into a single value which has the units of "points," where 1000 points represents the average environmental impact of a European in one year. Weighting is not used in this study.

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[2] A consequence of biogenic carbon not being included in the IPCC standard for this study is that it may obscure the impact of several critical assumptions regarding carbon neutrality of pulping liquor combustion during production of sulfate pulp for virgin-content paper towels. It also neglects the forestry impacts for paper towels. However, this study follows the IPCC method, which does not include biogenic carbon as it represents the scientific consensus on carbon accounting.

A multi-indicator impact assessment method was sought that could calculate other important impacts beyond global warming such as human health and ecosystem quality. IMPACT 2002+ was selected because it is an internationally accepted method for LCIA that includes characterization models from several well-respected LCIA methodologies. Furthermore, it has been used in another key hand drying study (the Excel study [14]).

This study includes results from IMPACT 2002+ midpoint categories in tabular format, but most of the graphical results are presented for the human health and ecosystem quality endpoint categories to facilitate a clear and simple comparison of environmental impact within these categories. The other two endpoint categories, climate change and resources, are not included in this study because they are very similar (although not identical) to GWP and cumulative energy demand (described below), and therefore are considered redundant.

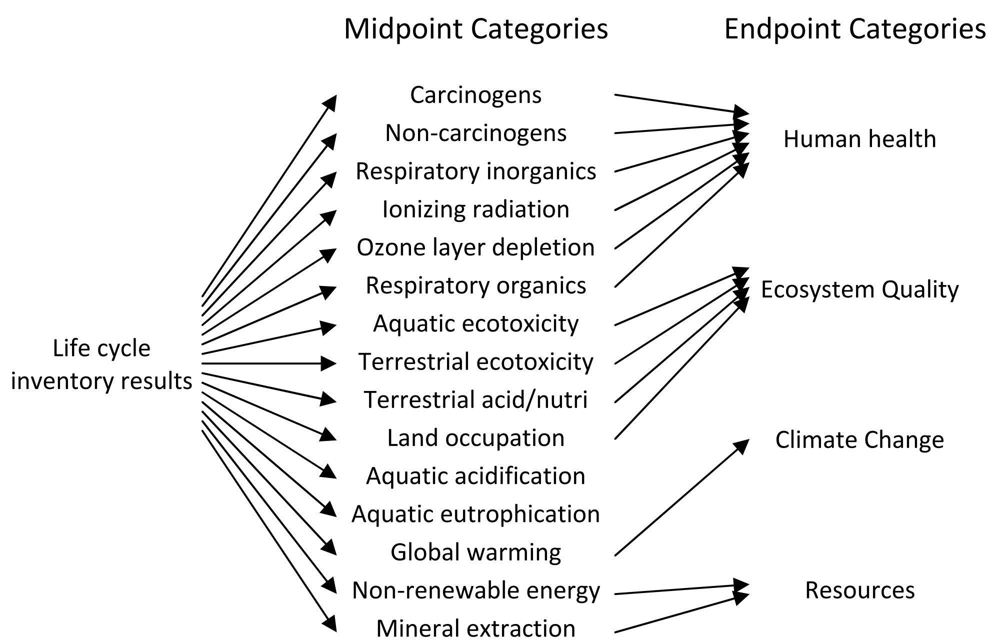


Figure 4 The 15 midpoint categories and four endpoint categories of IMPACT 2002+.

A limitation of applying the IMPACT 2002+ methodology is that it is focused on a European context, whereas the focus of this study is the United States. However, this assumption is acceptable given that multiple regions outside the US will be evaluated in sensitivity analyses and it is not constructive to use different LCIA methods for each region (particularly when they may not be available for all regions). Furthermore, IMPACT 2002+ has been deemed to be currently more internationally accepted than US-specific methods such as TRACI.

4.1.3 Cumulative energy demand

Cumulative energy demand (CED) [48] includes all direct and indirect energy consumption associated with a defined set of unit processes. It does not directly account for the impact of raw material consumption or emissions to the environment. Values for CED are measured in terms of energy (e.g.

joules). It is important to note that CED is a proxy metric for environmental impact and thus, it is not a formal impact assessment method, although it is commonly referred to as such and will be in this report. Like GWP and IMPACT 2002+, CED is a widely accepted methodology.

CED was selected as an LCIA methodology for this study because energy consumption is often the primary driver of environmental impact for electricity-intensive products such as hand dryers. Furthermore, the public is familiar with energy as a proxy metric of environmental impact because of the extensive marketing around energy consumption of consumer products. Cumulative energy demand is an extension of this type of thinking to the entire product life cycle and thus, is a natural metric for use in this study.

4.1.4 Water consumption and land occupation

Water consumption is calculated as an elementary flow in the life cycle inventory and land occupation is a midpoint category in the IMPACT 2002+ methodology. They are included as impact assessment metrics because they are particularly relevant to assessments of products made from natural resources (such as paper). Aside from presentation of results, however, they are not further assessed. Water consumption, in particular, is not a LCIA methodology, but rather a summation of water use (including turbine flows) that is calculated directly from drying system life cycle inventories.

4.2 Baseline analysis

4.2.1 Results by impact assessment methodology

Figure 5 shows the resulting GWP, broken down by life cycle stage, associated with drying one pair of hands. Both measured and reported dry times are included in Figure 5a and b, respectively. In both cases, the two Dyson Airblade™ hand dryer systems are associated with the lowest GWPs of all the hand-drying systems, followed by the XLERATOR® system. The standard dryer system, on the other hand, is associated with the highest. Since each dryer dries up to 350,000 pairs of hands over its life span, the impact from the production and end-of-life stages allocated to each pair of dry hands is very small; consequently, dryer impact is dominated by use and dryers with similar dry times (and power ratings) will have similar impacts. Cotton roll towel system impact is also dominated by use, which is driven by the washing of the towels. By contrast, materials and manufacturing have the largest impact for paper towels. Despite the different manufacturing processes, there is minimal difference between the virgin and the recycled paper towels because they this study assumes they use the same tissue manufacturing process, and pulp produced from waste paper has nearly the same GWP as pulp produced with virgin wood. It is difficult to assess exactly how this assumption impacts the results because the Kimberly-Clark study calculates at 30% *increase* in GWP impact for recycled paper towels over virgin paper towels [13], whereas the Paper Task Force [58] noted in a 1995 report on printing paper that deinked pulp production consumes less energy and more bleaching chemicals than bleached kraft pulp production. A consistency check is performed in Appendix 8A.6A.6, which compares the GWP results in Figure 5 with results from literature. The check indicates that there is variation in other published results of paper towel impacts, but the outcomes in this study are similar to those calculated in the Kimberly-Clark study. Improved inventory data on recycled paper towels would help to clarify these discrepancies among studies.

IMPACT 2002+ results, calculated using measured and reported dry times, are presented in Figure 6. Only human health and ecosystem quality are included because the other two endpoint categories, climate change and resources, are made redundant by this report's use of GWP and CED. Additionally, midpoint category outputs, used in the calculation of the endpoints, are included in Table 8. In these results, the impacts of the Dyson Airblade™ hand dryers are generally lower than those of the other drying systems: only the cotton roll towels are associated with lower impacts in the carcinogen, ionizing radiation, and mineral extraction midpoint categories. Roughly speaking, Dyson Airblade™ hand dryer impacts are followed by the XLERATOR® and cotton roll towel impacts, and then by the standard dryer and paper towel impacts; the exact order of the systems will ultimately depend on the midpoint category.

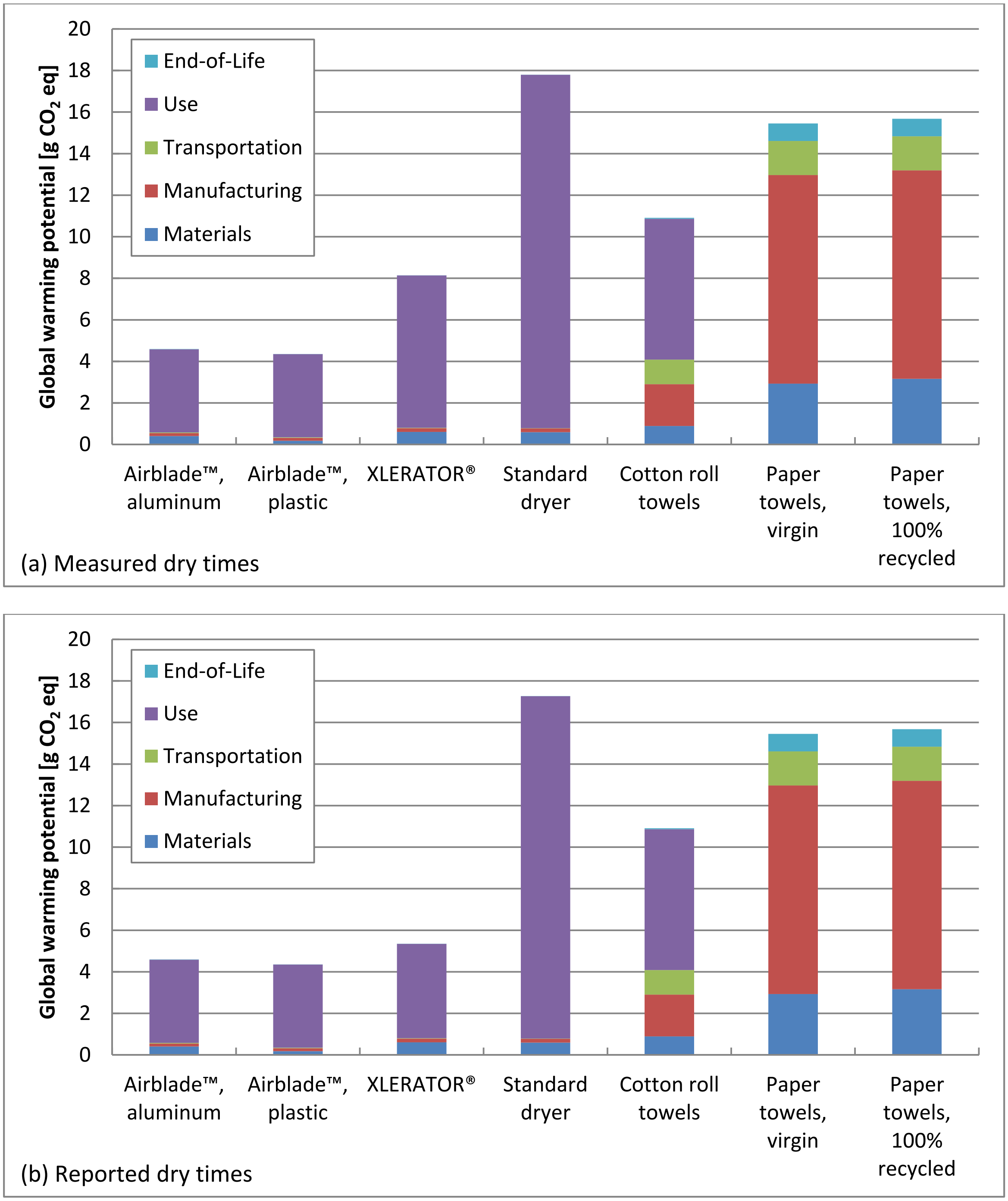


Figure 5 Global warming potential associated with drying a single pair of hands.

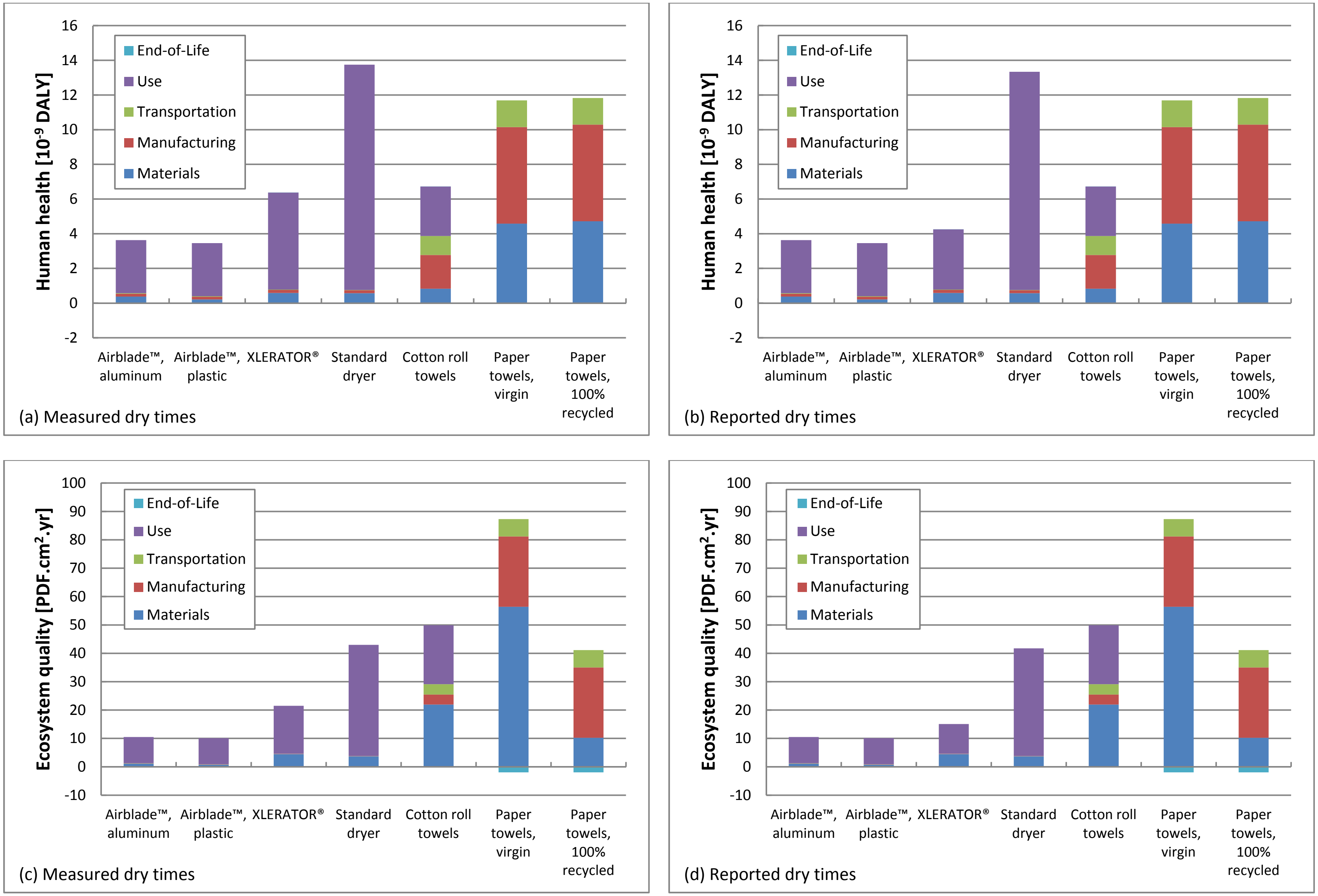


Figure 6 Impact associated with drying a single pair of hands based on impact 2002+ endpoints human health and ecosystem quality. (a) and (c) are calculated using measured dry times (in accordance with the NSF Protocol) and (b) and (d) are calculated using manufacturer reported dry times.

Table 8 Impact 2002+ midpoint category results for each drying system (given measured dry times).

IMPACT 2002+ midpoint categories	Units	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels, virgin	Paper towels, 100% recy.	Endpt. Category
Carcinogens	g C_2H_3Cl eq	0.277	0.272	0.486	1.111	0.205	0.525	0.525	HH
Non-carcinogens	g C_2H_3Cl eq	0.102	0.090	0.189	0.386	0.145	0.454	0.457	HH
Respiratory inorganics	g PM2.5 eq	3.63×10^{-3}	3.45×10^{-3}	6.33×10^{-3}	0.0135	8.16×10^{-3}	0.0126	0.0128	HH
Ionizing radiation	Bq C-14 eq	0.127	0.119	0.239	0.521	0.104	0.291	0.290	HH
Ozone layer depletion	g CFC-11 eq	1.43×10^{-7}	1.24×10^{-7}	2.68×10^{-7}	5.38×10^{-7}	1.03×10^{-6}	1.18×10^{-6}	1.21×10^{-6}	HH
Respiratory organics	g C_2H_4 eq	6.02×10^{-4}	5.81×10^{-4}	1.11×10^{-3}	2.27×10^{-3}	3.31×10^{-3}	4.38×10^{-3}	4.09×10^{-3}	HH
Aquatic ecotoxicity	g TEG water	486	462	1135	2197	935	1619	1628	EQ
Terrestrial ecotoxicity	g TEG soil	118	113	243	484	290	410	417	EQ
Terrestrial acid/nutri	g SO_2 eq	0.0757	0.0725	0.136	0.293	0.221	0.291	0.298	EQ
Land occupation	cm^2org.arable	0.102	0.094	0.227	0.478	22.1	45.0	21.1	EQ
Aquatic acidification	g SO_2 eq	0.0308	0.0297	0.0551	0.1210	0.0499	0.0812	0.0822	—
Aquatic eutrophication	g PO_4 P-lim	2.66×10^{-4}	2.45×10^{-4}	2.28×10^{-3}	2.80×10^{-3}	2.03×10^{-3}	4.05×10^{-3}	4.06×10^{-3}	—
Global warming	g CO_2 eq	4.44	4.19	7.85	17.2	10.2	14.6	14.8	CC
Non-renewable energy	kJ primary	72.1	69.2	130	285	171	245	247	RE
Mineral extraction	kJ surplus	0.162	0.137	0.170	0.216	0.062	0.280	0.277	RE

Endpoint categories: HH – human health; EQ – ecosystem quality; CC – climate change; RE – resources.

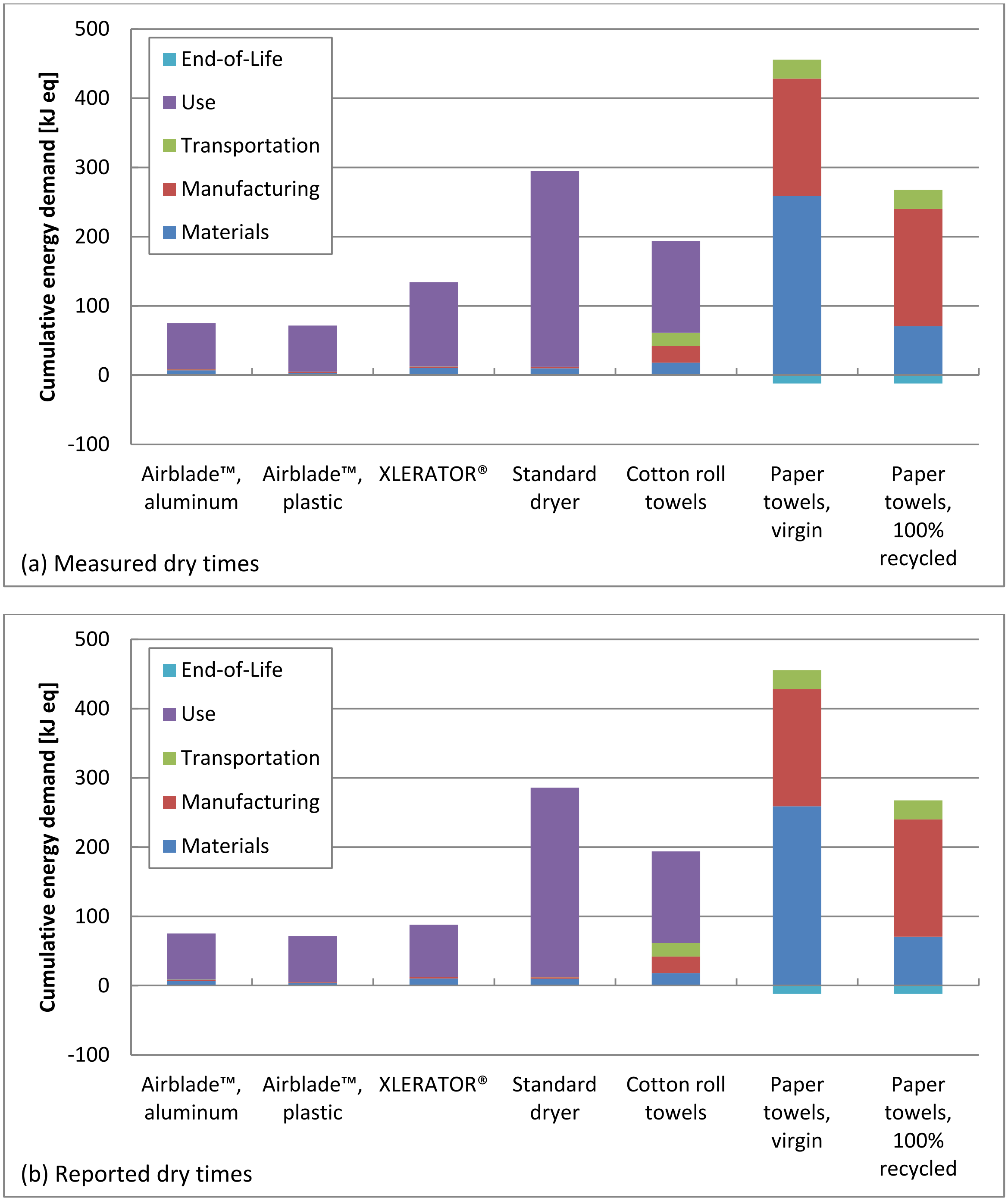


Figure 7 Cumulative energy demand associated with drying a single pair of hands, assuming (a) measured dry times and (b) reported dry times.

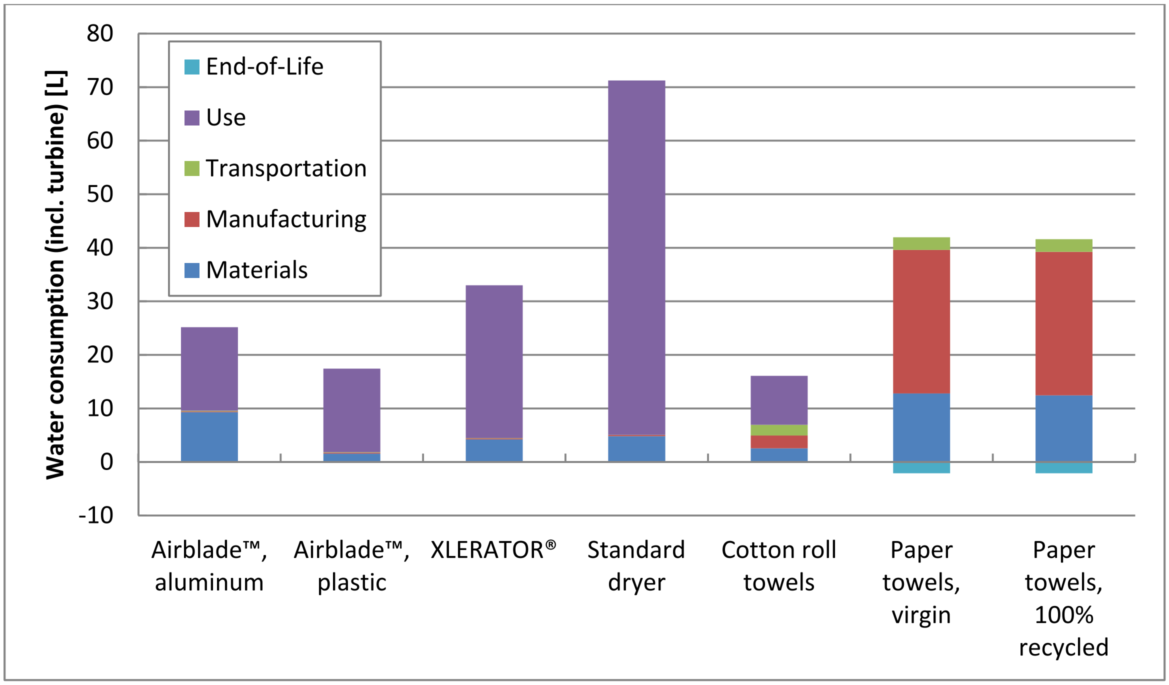


Figure 8 Water consumption associated with drying a single pair of hands (calculated from life cycle inventories based on measured dry times).

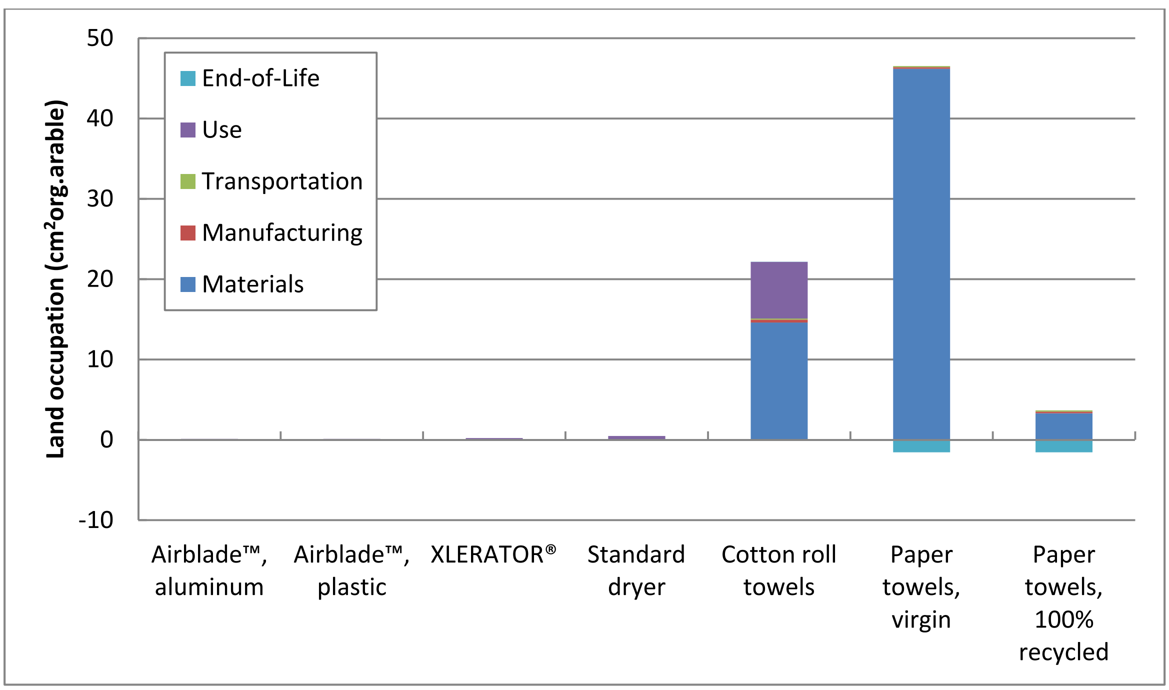


Figure 9 Land occupation (IMPACT 2002+ midpoint) associated with drying a single pair of hands (calculated based on measured dry times).

CED results, also calculated using measured and reported dry times, are presented in Figure 7. Again, the high-speed dryer systems are shown to have the lowest impacts, and the paper towel and the standard dryer systems the highest, with the cotton roll towel system falling somewhere in between. In the case of CED, virgin paper towels have the higher impact because the methodology accounts for the energy embodied in virgin wood.

Results from water consumption and land occupation are shown in Figures 8 and 9, respectively, for measured dry times only. Water consumption is calculated directly from the life cycle inventories, and land occupation is a midpoint category within IMPACT 2002+ and contributes to the ecosystem quality endpoint category.

4.2.2 Endpoint category normalization

Some LCIA methodologies, in particular those concerning multiple issues such as IMPACT 2002+, have an additional normalization step in which the results of endpoint categories are divided by a factor before being weighted and combined into a single score. In the case of IMPACT 2002+, the damage assessments are normalized by dividing the impact by the total impact of all substances within a specific category that a person living in Europe is exposed to over one year [50]. This normalization enables a comparison of the four endpoint categories so one can see which have the greatest effect on an average European. Figure 10 shows the results of this normalization for the two endpoint categories in Figure 6 as well as for the other endpoint categories, climate change and resources. The results indicate that human health, climate change, and resources have approximately the same relative impact while the impact of ecosystem quality is much less.

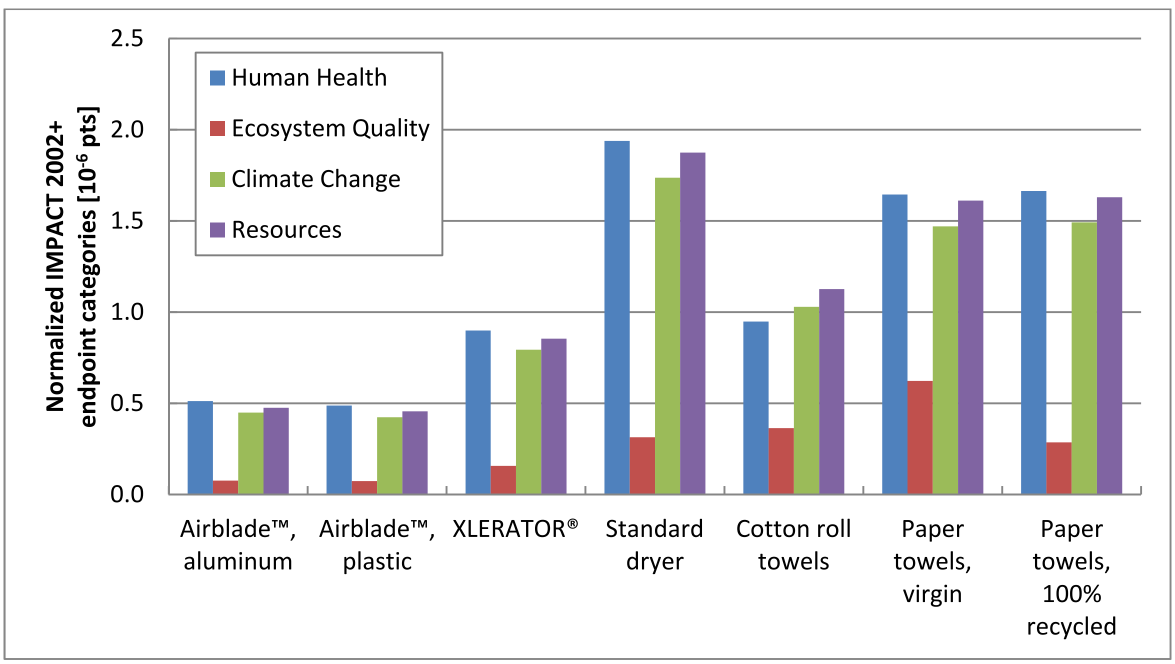


Figure 10 IMPACT 2002+ endpoint categories after normalization of results given measured dry times.

4.2.3 Rank order comparison

Drying system baseline results for measured dry times are compared in Table 9 by rank ordering the systems. (Rank order for measured dry times is slightly different for the human health and water consumption impact categories.) Systems are assigned the same rank if the difference between their impacts is within 10% of the smaller of the two numbers. The plastic Dyson Airblade™ hand dryer has the lowest impact for all of the metrics, followed by the aluminum Dyson Airblade™ hand dryer and the XLERATOR® dryer for all metrics except water consumption, where the impact of the cotton roll towels is essentially equivalent to that of the plastic Dyson Airblade™. Thus, the rank order of the top three products is nearly independent of the method used to calculate impact. The rank order of the standard dryer and the towels, however, is more strongly dependent on the impact assessment method, although a few generalizations can be made: the standard dryer and virgin paper towel systems are almost consistently associated with the highest impact, regardless of impact assessment method; as such, cotton roll towel impact is always less than virgin paper towel impact, as is that of the recycled paper towels. The significance of the difference between drying system environmental impact values is later evaluated in the scenario uncertainty analysis (Section 5.2.1) and the bill of activities uncertainty analysis (Section 5.2.2)

Table 9 Rank order of environmental impact of the products using the baseline scenario and measured dry times for all of the impact assessment metrics (1 = lowest impact, 7 = highest impact).

Product system	Global warming potential	Human health	Ecosystem quality	Cumulative energy demand	Water consumption	Land occupation
Airblade™, aluminum	1	1	1	1	3	1
Airblade™, plastic	1	1	1	1	1	1
XLERATOR®	3	3	3	3	4	3
Standard dryer	7	7	4	6	7	4
Cotton roll towels	4	3	6	4	1	6
Paper towels, virgin	5	5	7	7	5	7
Paper towels, 100% recy.	5	5	4	5	5	5

4.3 Additional product life cycles

Each drying system is comprised of multiple products that are required to fulfill a functional unit (see Table 1). Global warming potential and other impact results can therefore be broken down not only by life cycle stage, but also by these different products. Figure 11 shows the portion of each drying system's GWP attributed to each of these products. For dryers, the only other product is packaging, which accounts for a very small fraction of total impact. Slightly more of towel GWPs are associated with packaging, dispensers, waste bins, and bin liners, but the majority of the impact is still due to the towels themselves.

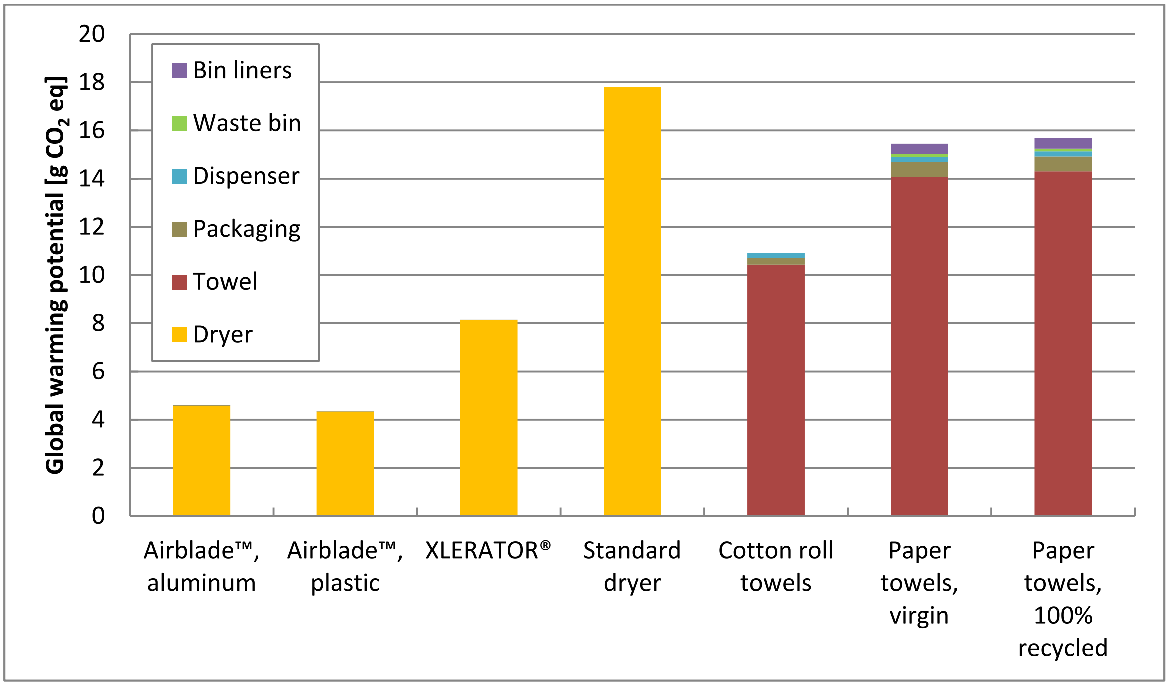


Figure 11 GWP of hand-drying systems, broken down by product.

4.4 Contribution analysis for individual products

This section includes a closer look at the environmental impact of the different hand-drying systems, specifically the contributions to and drivers of that impact.

4.4.1 Dryers

As can be seen from Figure 5, the materials, manufacturing, transportation, and end-of-life stages of hand dryers comprise a small fraction of the total impact associated with drying one pair of hands—around 4% to 13% of GWP when calculated using measured dry times. Consequently, altering the assumptions related to these life cycle stages, such as accounting for scrap loss in XLERATOR® and standard dryer production or locating production in China, will have minimal affect on the final impact results. Nonetheless, it is still important to more closely evaluate these stages—materials and manufacturing in particular as they are much higher than the other two—because they are collectively responsible for as much as 283 kg CO_2 eq before their impacts are allocated among the 350,000 hand-dryings that take place during a dryer's lifetime. Additional evaluation will also help to inform product design decisions.

The production (i.e. materials and manufacturing) stage GWP, before allocation among lifetime uses, is broken down in Figure 12 for the aluminum and plastic Dyson Airblade™ hand dryers, and in Figures 13 and 14 for the XLERATOR® and standard dryers, respectively. As can be seen from Figure 12, over 75% of the impact is due to three processes: electricity, steel sheet, and aluminum or PC/ABS. The steel sheet and aluminum or PC/ABS dominate impact because of their high masses relative to those of other dryer components: aluminum and PC/ABS are used for the dryer covers and steel sheet for the dryer back plate plus, in the case of the plastic dryer, reinforcement brackets. Electricity, on the other hand, dominates because the dryer is assumed to be manufactured in China and therefore uses a carbon-intensive grid mix. The remaining components, which form the dryer motor, ducts, electronics, and so forth, are less than 25% of production impact.

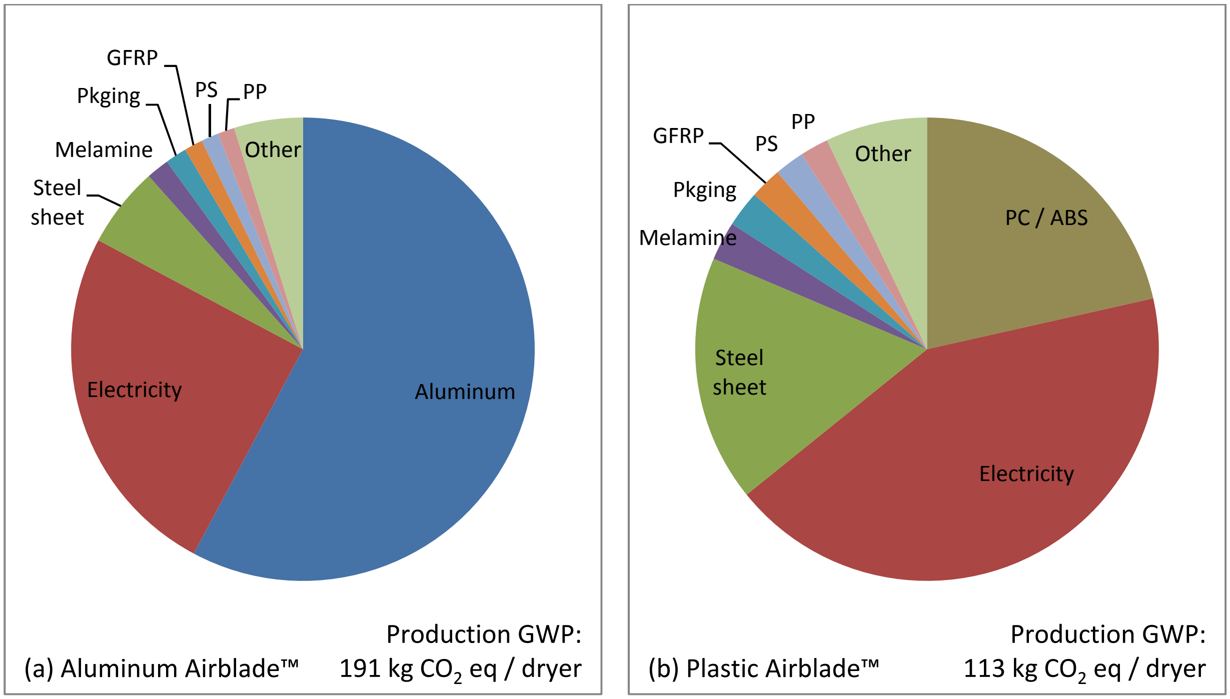


Figure 12 Breakdown of production (materials & manufacturing) phase GWP for (a) aluminum and (b) plastic Dyson Airblade™ hand dryers.

Over half the production GWPs of the XLERATOR® and standard dryers are due to the dryers' control and optics assemblies (Figures 13 and 14). These assemblies, however, account for less than 3% of dryer mass (see Table 19 in the Appendix). Given their outsized impact in proportion to their masses as well as relative to Dyson Airblade™ hand dryer results (the Dyson Airblade™ hand dryer's circuit boards, by contrast, account for less than 2% of production GWP), there is an opportunity to take a closer look at the materials and manufacturing processes that go into producing these assemblies. Specifically, more information about the assemblies in the XLERATOR® and standard dryers is needed because their inventories are currently modeled with a generic unit process from ecoinvent, "Electronic component, active, unspecified," which may not accurately represent them; by contrast, more details are known about the Dyson Airblade™ hand dryer's electronic components and a more specific unit process, "Printed wiring board, through-hole, lead-free surface," is used. The use of the generic ecoinvent process to model the electronics of the XLERATOR® and standard dryers is examined more closely in Section 5.1.6 as part of the sensitivity analysis.

Electricity used in manufacturing the XLERATOR® and the standard dryers represents the second largest contributors to the production stage GWP, consistent with the charts in Figure 12. Since the XLERATOR®

cover is assumed to be a combination of the dryer's three different covers—stainless steel, plastic, and chrome finish—no one material dominates by mass.

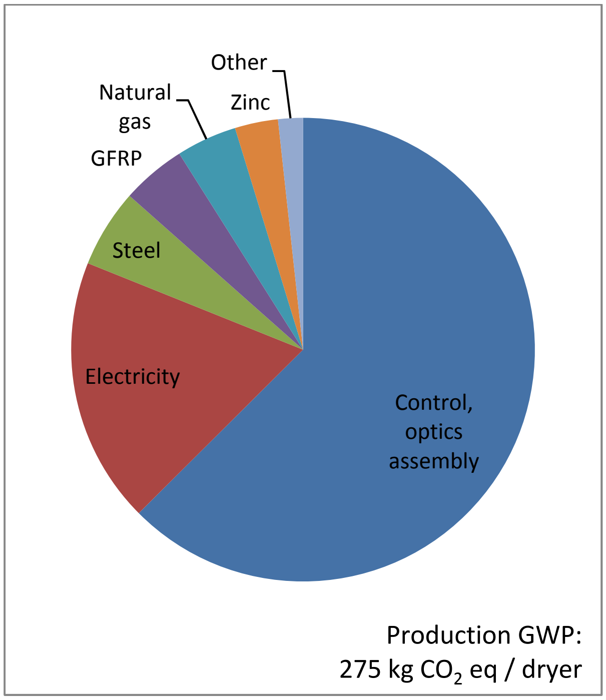


Figure 13 Breakdown of production phase GWP for the XLERATOR® dryer.

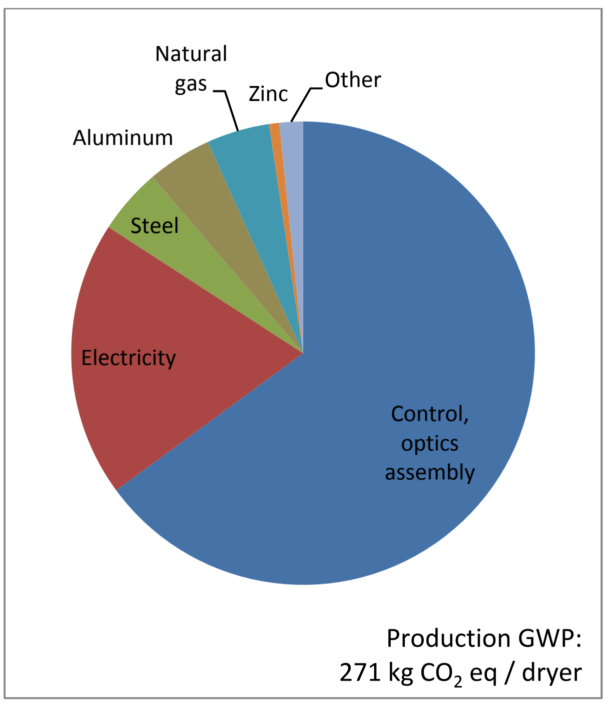


Figure 14 Breakdown of production phase GWP for a standard dryer.

As noted earlier, altering the assumptions related to the production, transportation, and end-of-life stages will have minimal affect on the total GWP associated with drying one pair of hands with a hand dryer. Assumptions related to the use phase, however, can significantly change GWP because the use phase dominates total impact. Use phase impact is driven entirely by electricity consumption, most of which occurs when the dryer is in-use rather than when it is spinning down or on standby (Figure 15). The sensitivity analysis (Section 5.1) includes an assessment of use intensity, which defines how long users wait to dry their hands and thereby affects use stage GWP; power consumption is considered fixed for this study.

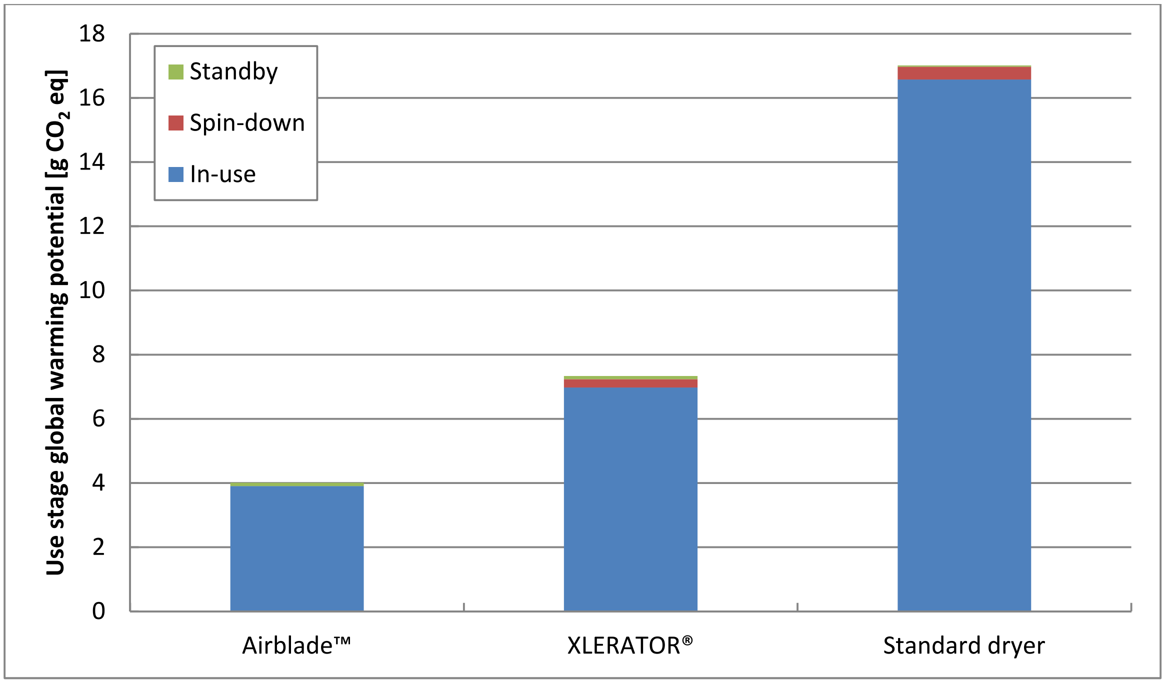


Figure 15 Breakdown of dryer use stage GWP.

4.4.2 Cotton roll towels

Like dryers, cotton roll towels have their production, transportation, and end-of-life stage impacts allocated across multiple uses. For cotton roll towels, this is the 103 times [12] they can be reused before disposal. Producing the equivalent of one pull on a cotton towel roll, however, still emits 253 g CO_2 eq. The breakdown of cotton roll towel production (Figure 16) shows that weaving accounts for a large fraction of GWP on account of its energy requirements, whereas sizing, the addition of starch to yarn to facilitate weaving, is less than 1% of the total.

Over half of the total GWP associated with using a cotton roll towel to dry a pair of hands, though, is due to the use stage—specifically laundering the towels (Figure 5). Within this process, the natural gas required to heat the water and thermally disinfect the towels contributes the most to use-phase impact (Figure 17); transportation to and from laundry facilities is not included in the figure.

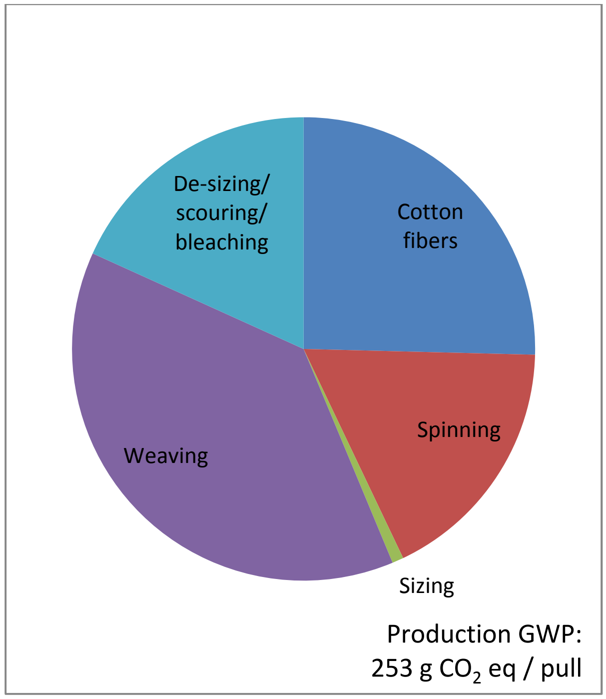


Figure 16 GWP breakdown of producing the equivalent of one pull on a cotton towel roll.

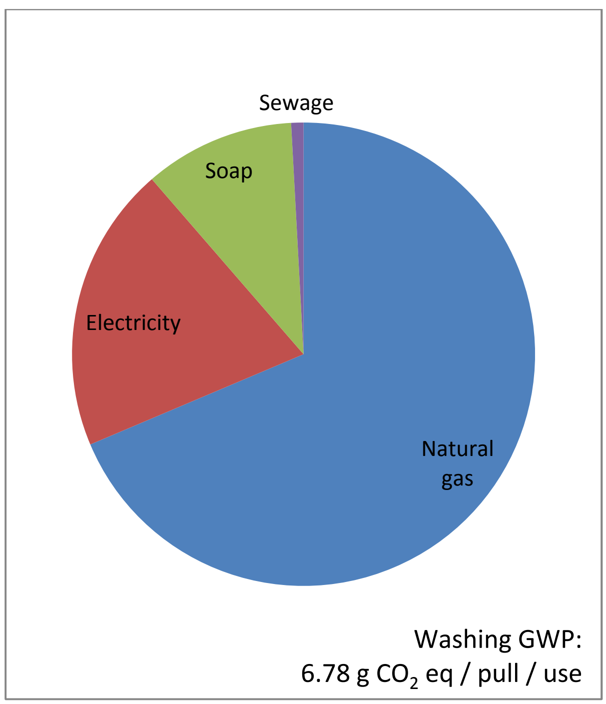


Figure 17 GWP breakdown of washing cotton roll towel (use stage impact).

4.4.3 Paper towels

Paper towels contribute the most to system impact in their respective hand-drying systems: as Figure 11 shows, packaging, dispensers, waste bins, and bin liners account for less than 10% of total GWP. Most of this impact, in turn, can be attributed to pulp production and towel manufacturing (Figure 5). The results in Figures 5–9 indicate that paper towels with recycled content have a lower impact than virgin paper towels for four of the six metrics. The extent of the difference in impact depends on the metric: in the case of GWP, human health, and water consumption, the difference between the impacts of the two systems is less than 10%; this is reflected in the drying system rankings in Table 9 where both paper towel systems are assigned the same rank. This conclusion, naturally, is subject to pulping process data and the assumption that the recycled pulping process is the same as the virgin pulping process. The conclusion could potentially change if processes other than sulfate pulp are used and if inventory data on a recycled pulping process were used. The difference between the two systems is more pronounced for ecosystem quality, CED, and land occupation. Virgin paper towels have a higher CED because the metric accounts for the energy embodied in the wood. Likewise, this need for wood contributes to the land occupation metric, which itself is part of the ecosystem quality calculation in the IMPACT 2002+ LCIA methodology (see [50]).

Figures 18 and 19 respectively break down the GWP and CED associated with paper towel production into pulp manufacturing and the processes required to produce paper towels from pulp. Pulp manufacturing is in turn broken down into the impact due to wood or waste paper and the manufacturing process. As the charts show, the GWP breakdowns of both paper towel types are very similar, partly because the GWP LCIA methodology does not account for biogenic carbon embodied in the wood. The renewable energy content in the paper (analogous to biogenic carbon), however, is accounted for in the CED LCIA methodology: the energy embodied in the wood used in manufacturing virgin pulp increases the pulp's contribution to CED as well as the overall impact (see Figure 7).

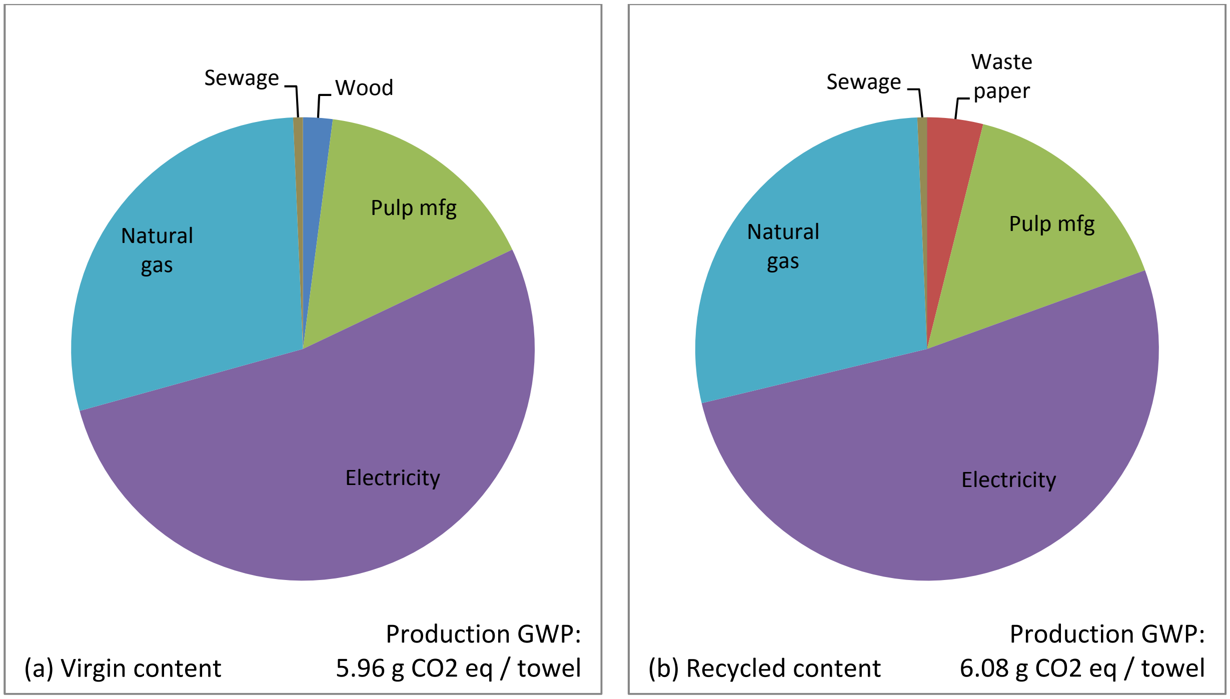


Figure 18 GWP breakdown of paper towel production from (a) virgin and (b) recycled content.

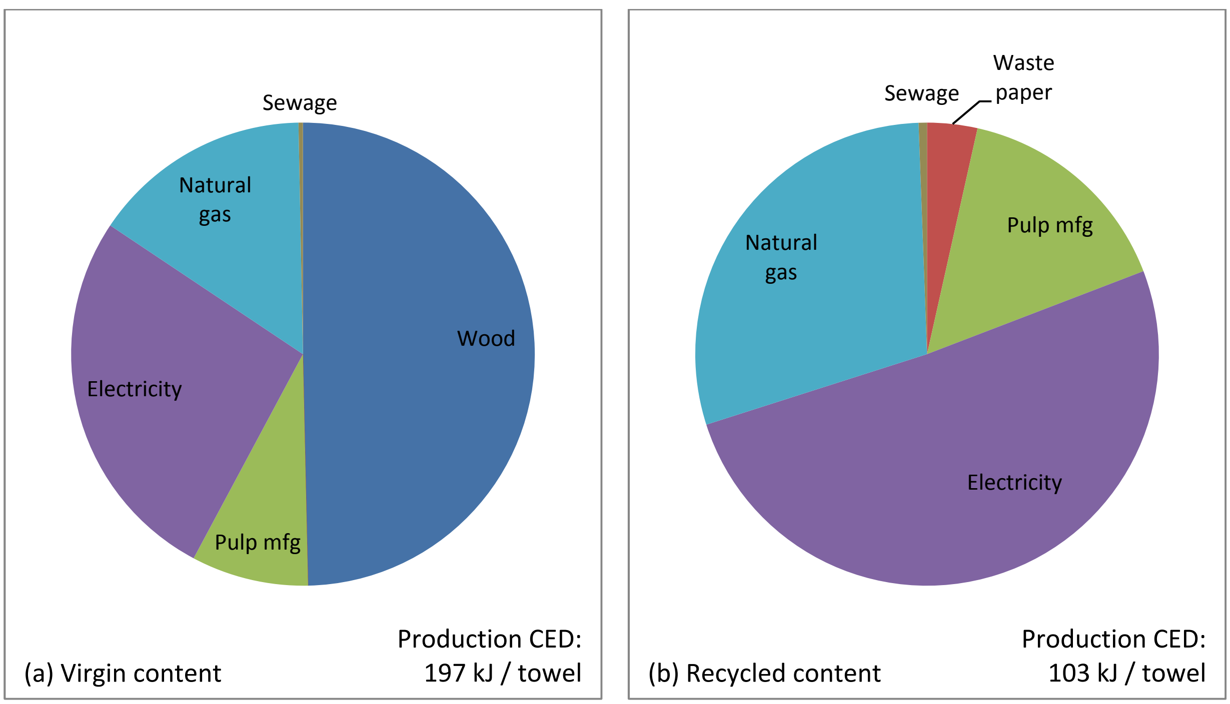


Figure 19 CED breakdown of paper towel production from (a) virgin and (b) recycled content.

5 Life cycle interpretation

The life cycle interpretation section focuses on understanding the life cycle impact assessment results within the context of the analysis' limitations, uncertainty, and assumptions. This is accomplished with sensitivity and uncertainty analyses. The former evaluates variability in baseline scenario assumptions, one parameter at a time, while the latter explores simultaneous variation of parameters as well as addresses uncertainty in the bill of activities data. A pedigree matrix and Monte Carlo simulation are respectively used to quantify and to propagate uncertainties in the analysis.

5.1 Sensitivity analysis

One scenario alone cannot account for the wide range of usage patterns or other parameters that can affect environmental impact. Sensitivity analyses are therefore conducted to address the variability in the baseline scenario's assumptions. Assumptions addressed include:

- Lifetime usage
- Manufacturing phase electric grid mix
- Use phase electric grid mix
- Use intensity
- End-of-life scenario
- Dryer electronics unit process
- Cotton roll towel reuses
- Paper towel mass
- Pulp manufacturing process
- End-of-life allocation methodology for recycled content in paper towels
- Manufacturing location
- Use location

In these analyses, the hand-drying system GWPs are compared under different scenarios to assess the robustness of the observation in Section 4.2 that high-speed dryers have the lowest impact of all the systems. These analyses are also used to evaluate how different factors affect each system's environmental burden and which of those factors matter the most. The results indicate that electric grid mix and use intensity (Sections 5.1.2 – 5.1.4) exert the largest influence on drying system GWP. Later, a Monte Carlo simulation (Section 5.2.1) is used to evaluate the uncertainty surrounding the baseline scenario assumptions. Dryer impact is calculated assuming measured dry time as assessed with the NSF Protocol P335.

5.1.1 Lifetime usage

The baseline scenario assumes a lifetime usage of 350,000 pairs of hands dried over a 5-year time frame [26, 27]. The actual number of uses, however, could be higher or lower, depending on washroom traffic: for instance, the Excel study assumes 260,000 pairs of hands are dried over 10 years [14]. Figure 20 illustrates the effect of both lower and higher usage over the 5-year time frame. Increasing usage reduces impact because the production and end-of-life burdens of the dryer (or dispenser, packaging, etc.) are spread over more pairs of hands. For the aluminum Dyson Airblade™ hand dryer system, an increase in usage to 450,000 results in a less than 4% decrease in impact; this change is even lower for the other systems—as little as 0.4% for the cotton roll towel system. Thus, changing lifetime usage alone is not sufficient to favor either cotton or paper towels over the high-speed hand dryers.

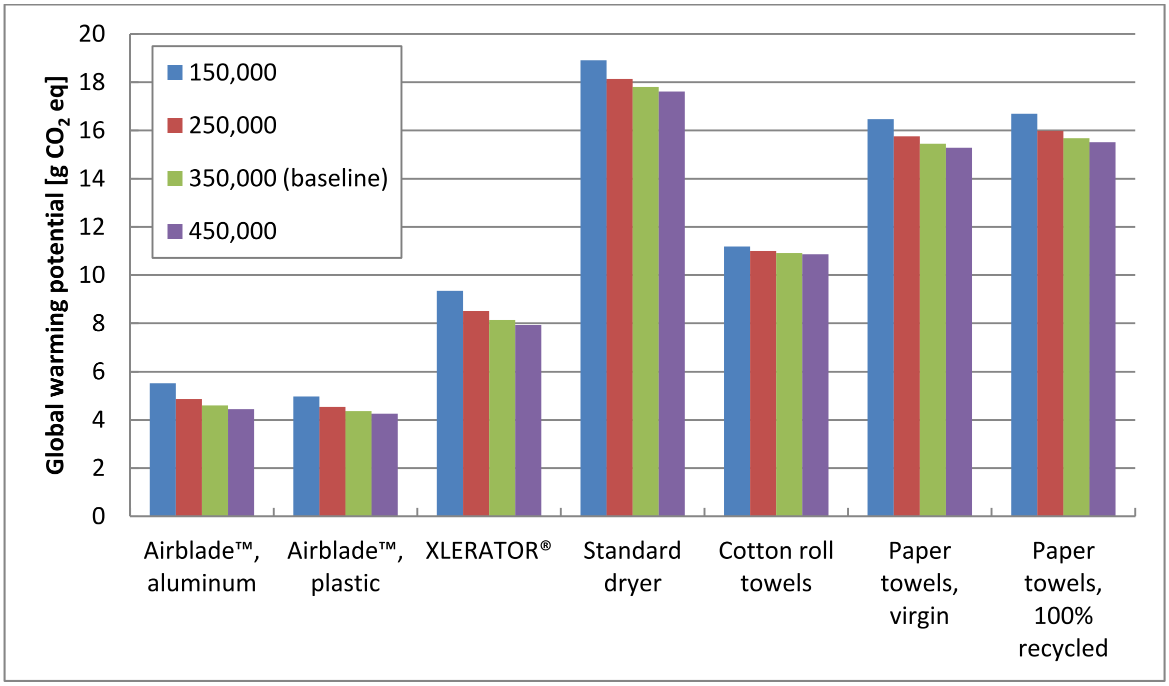


Figure 20 Effect of product lifetime usage on drying system GWP.

5.1.2 Manufacturing stage electric grid mix

This next sensitivity analysis investigates the consequences of altering the manufacturing stage electric grid mix by assessing drying system GWP given two hypothetical extremes: a carbon-intensive all-coal grid and a greener all-hydropower grid. A hypothetical all-nuclear grid is also added for comparison. The analysis accounts for the assumption that paper towels are manufactured in a different location from dryers and cotton roll towels by assuming the hypothetical grid mixes use technologies appropriate for each drying system's manufacturing location. That is, the hypothetical all-coal grid for dryer production assumes Chinese technology—and thereby associated emissions factors—whereas the all-coal grid for paper towel manufacturing assumes US technology.

As seen from the results in Figure 21, altering the manufacturing stage grid mix minimally affects dryer GWP because this stage accounts for a very small fraction of overall environmental impact (see Figure 5). The opposite is true of paper towels, which derive the majority of their impact from materials and manufacturing. The use of a greener grid, however, cannot completely eliminate paper towel emissions because some of the emissions are derived from the pulping process, as well as from natural gas used in tissue manufacturing (see Figure 18). Cotton roll towels fall somewhere in between these two extremes because while their production accounts for a larger fraction of GWP compared to the dryers, over 50% of impact is due to the use stage.

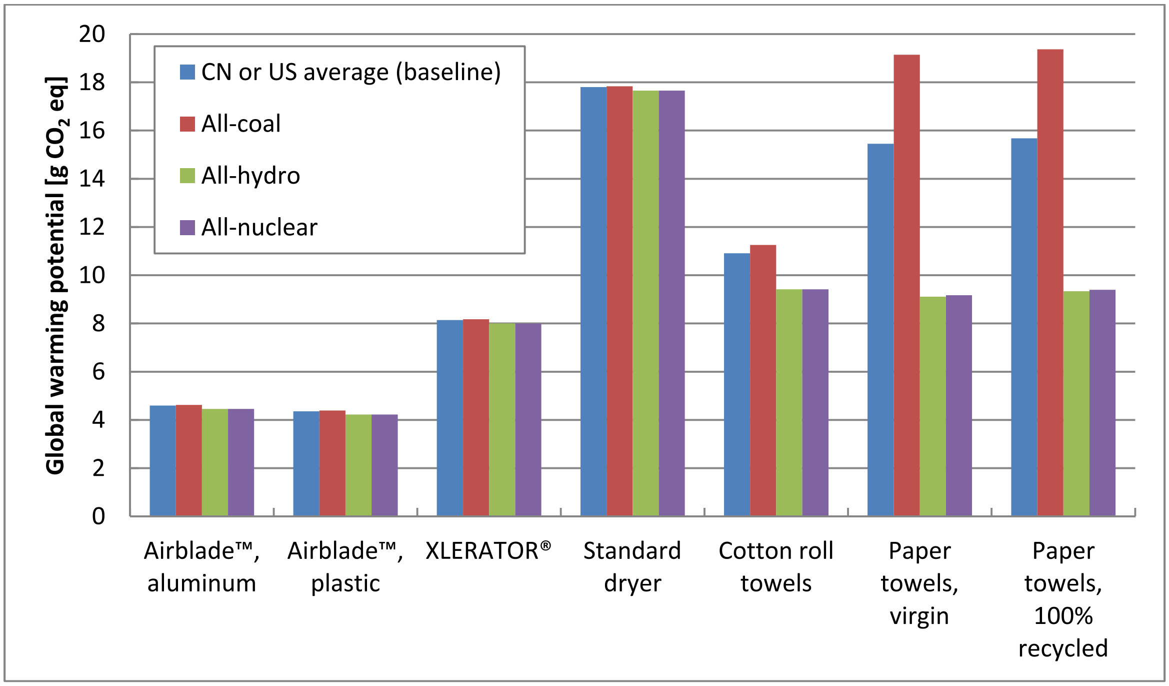


Figure 21 Effect of altering manufacturing phase grid mix on drying system GWP.

5.1.3 Use phase electric grid mix

In addition to the manufacturing stage electric grid mix analysis, a use stage grid mix analysis is also conducted. The latter is accomplished in similar fashion with hypothetical all-coal, all-hydropower, and all-nuclear grids used to assess the consequences of varying grid mix on drying system GWP. Since use stage is assumed to take place in the US, all hypothetical grids assume US technology and emissions factors. Only the impacts of dryer and cotton roll towel systems are affected: the impacts of the paper towel systems do not change as no use-stage electricity consumption is associated with those systems.

The effect of the different grids is shown in Figure 22. Since the US relies on coal for around 45% of its grid [51], the baseline is already carbon-intensive. Thus, GWP increases on average 53% for the high-speed dryers when they are run on an all-coal grid. By contrast, hydropower and nuclear grids are much less carbon-intensive, which allows dryer impact to decrease dramatically. While cotton roll towel impact also decreases, the change is less significant than for the hand dryers. The majority of the use-stage impact for cotton roll towels is derived from natural gas (see Figure 17) and thereby unaffected by changes in grid mix.

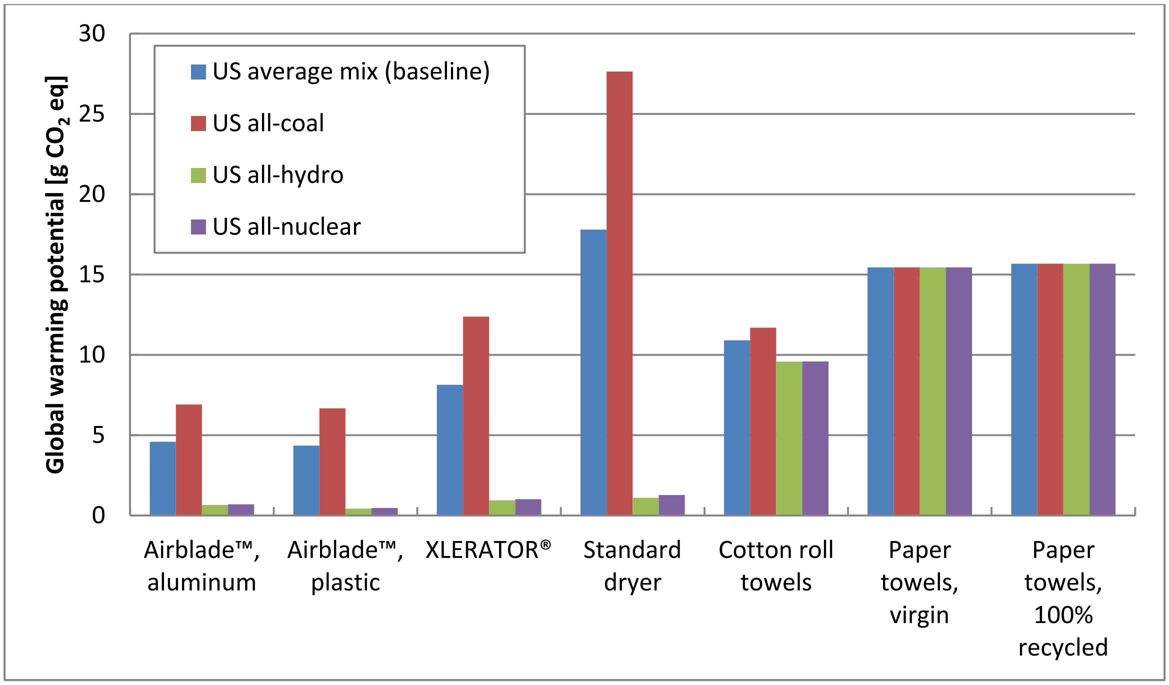


Figure 22 Effect of use phase electric grid mix on drying system GWP.

5.1.4 Use intensity

Also important is the use intensity of each hand-drying system. Use intensity depends heavily on the systems' users—how long they are willing to wait when using a hand dryer or how many towels they take to wipe their hands. Three use intensity scenarios are examined in this sensitivity analysis: a moderate scenario, which is equivalent to the baseline assumptions (including measured dry times for the hand dryers), and a low and a high scenario, which respectively represent 50% less or 25% more than the moderate scenario (Table 10). Results for these scenarios, shown in Figure 23 clearly illustrate the significant effect the use intensity assumption has on a hand-drying system's GWP.

Table 10 Use intensity scenarios.

Drying system	Low	Moderate (Baseline)	High
Airblade™	6 sec	12 sec	15 sec
XLERATOR®	10 sec	20 sec	25 sec
Standard warm air dryer	16 sec	31 sec	39 sec
Cotton roll towels	1 pull	1 pull	2 pulls
Paper towels	1 towel	2 towels	3 towels

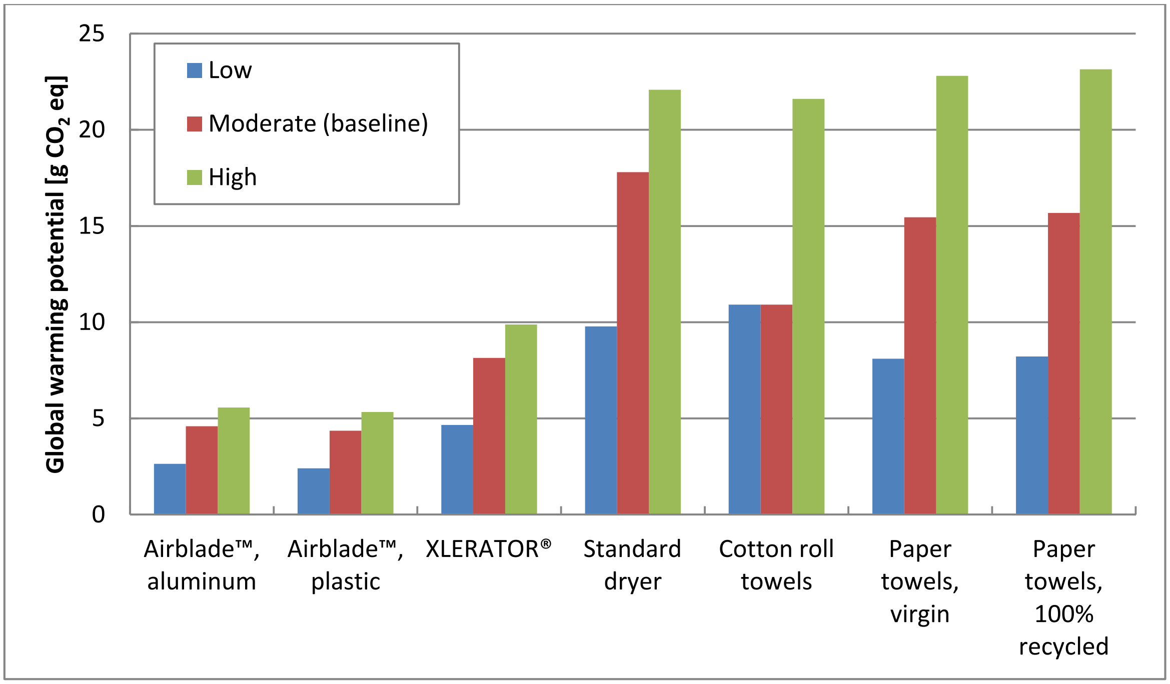


Figure 23 Effect of use intensity on drying system GWP.

5.1.5 End-of-life scenario

This next sensitivity analysis evaluates the effect of different end-of-life scenarios in the US. These scenarios investigate energy recovery from incineration, the fraction of incinerated waste, and composting. In the baseline case, 76.7% of cardboard packaging is recycled, with 19% of the remaining cardboard and all other waste incinerated and 81% sent to the landfill [30]. The three hypothetical alternative scenarios assume 1) landfilling 100% of the waste, 2) incinerating 100% of the waste, and 3) the baseline case with 100% composting for the towels.

The composting unit process inventory assumes each kilogram of waste results in 350 grams of compost, which displaces 18.4 grams of synthetic fertilizer (based on data from [32, 47]). The towel drying systems are credited with the emissions that would have resulted from the production of the synthetic fertilizer. Energy recovery at the incineration facility and from the combustion of methane captured at the landfill is assumed for the base case and all alternative scenarios. The exact details of these processes are included in Appendix A.2. Only cardboard packaging is assumed to be recycled.

Figure 24 illustrates the consequences of the different end-of-life scenarios. Since the burden associated with hand dryer end-of-life is such a small fraction of overall impact, there is almost no difference whether the dryers are sent to the landfill or incinerated. The choice of landfill versus incineration also has minimal effect on the GWP of the cotton roll towel and paper towel systems. Sending 100% of the waste to the landfill results in slightly lower emissions due to the combination of methane capture and energy recovery; sending 100% of the waste to be incinerated actually results in slightly increased emissions. Composting can significantly reduce a paper towel's end-of-life burden because of the avoided production of synthetic fertilizer.

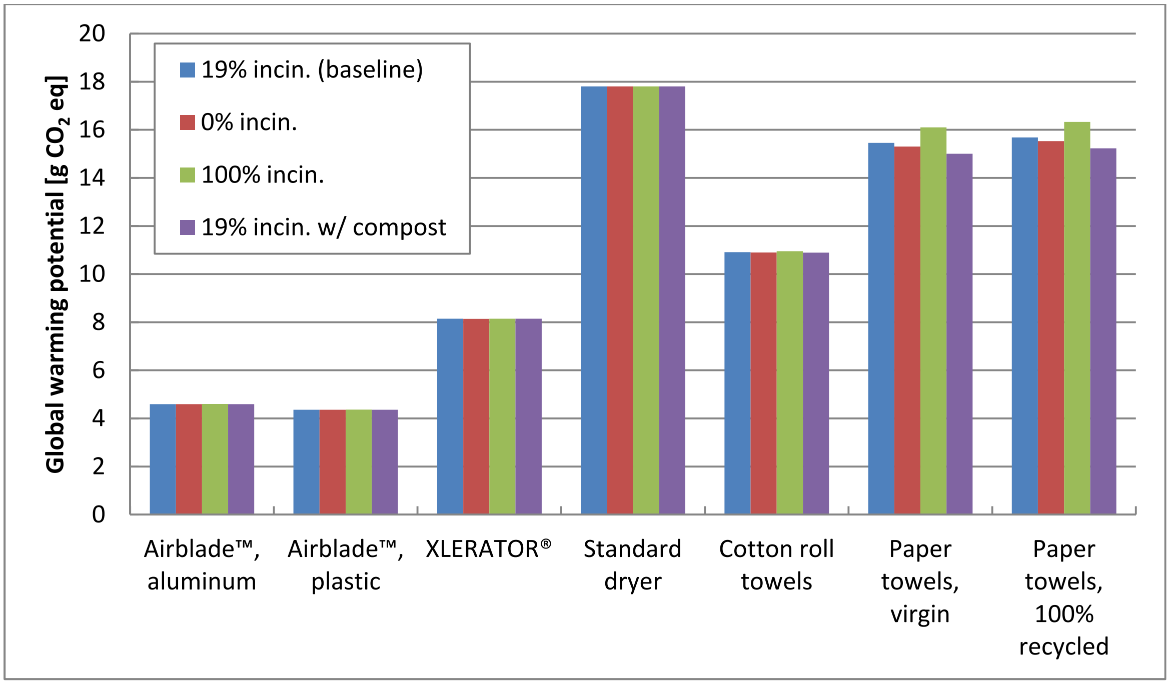
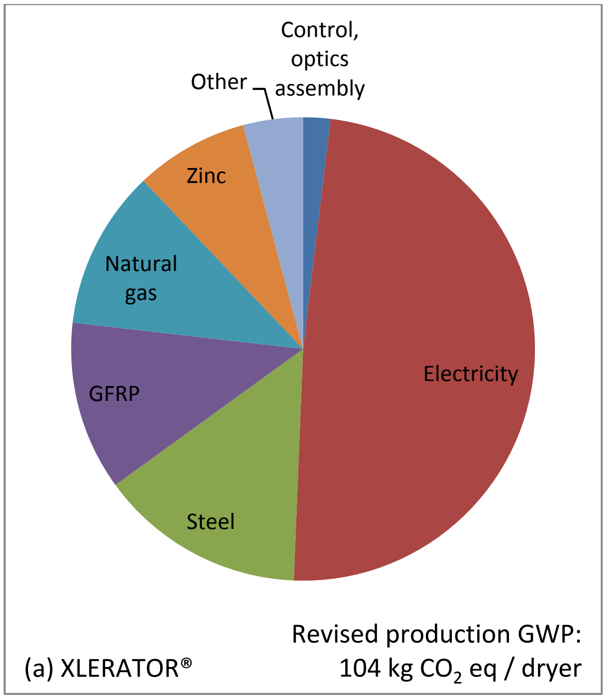


Figure 24 Effect of fraction of waste incinerated on drying system GWP.

5.1.6 Dryer electronics unit process

The next five sensitivity analyses examine parameters that concern at most two of the seven drying systems; the other systems remain unchanged. The first of these analyses addresses the choice of ecoinvent unit processes for the control and optics assemblies in the XLERATOR® and the standard dryers. As seen in the dryer contribution analysis (Section 4.4.1), these assemblies account for a disproportionately large fraction of each dryer's production GWP (Figures 13 and 14), especially when compared to the much smaller impact of the Dyson Airblade™ hand dryer's circuit boards (aggregated under "other" in Figure 12). This is due to the choice of a generic unit process, "Electronic component, active, unspecified," to represent the control and optics assemblies; a more specific unit process, "Printed wiring board, through-hole, lead-free surface," is used for the Dyson Airblade™ hand dryer's inventory. Figure 25 illustrates the consequences of substituting the printed wiring board (PWB) unit process for the generic unit process in the XLERATOR® and standard dryer inventories. This substitution reduces dryer production impact from 275 to 104 kg CO_2 for the XLERATOR® dryer and from 270 to 100 kg CO_2 for the standard dryer (cf. Figures 13 and 14). The production stage, however, accounts for only a small fraction of the GWP associated with a functional unit (see Figure 5); thus, changing production impact has minimal effect on total functional unit GWP, as illustrated in Figure 26.



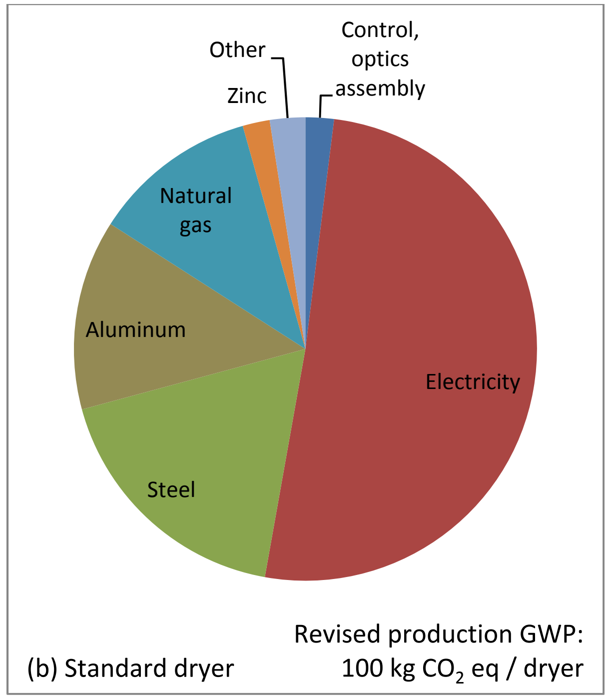


Figure 25 Revised production GWP breakdown from altering the ecoinvent unit process used to model control and optics assemblies for the (a) XLERATOR® and (b) standard dryers.

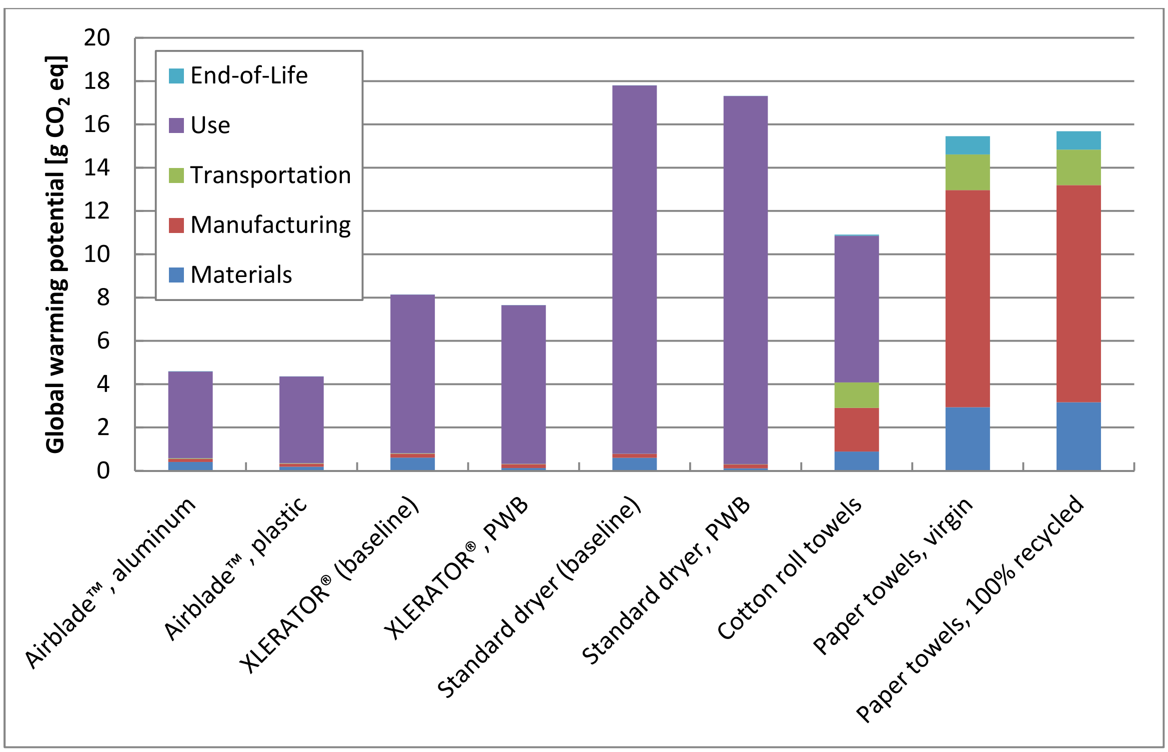


Figure 26 Effect of altering ecoinvent unit process used to model control and optics assemblies on GWP associated with a functional unit.

5.1.7 Cotton roll towel reuses

The number of times a cotton roll towel can be laundered and reused will affect how much of its production burden is allocated to drying a single pair of hands. This is in contrast to lifetime usage (Section 5.1.1), which addressed the lifetime of the towel dispenser. Figure 27 shows the consequences of laundering and reusing a towel as few as 70 times or as many as 130 times [12]; in the baseline scenario, cotton roll towels are reused 103 times

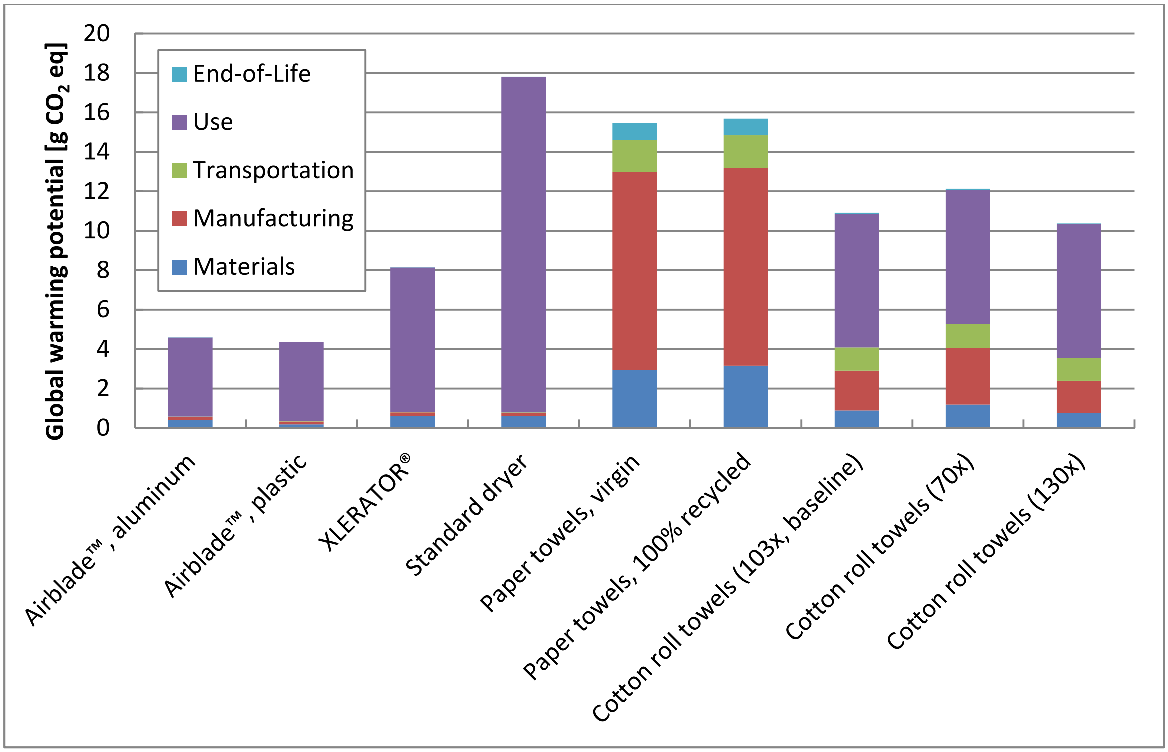


Figure 27 Effect of changing number of times cotton roll towel are laundered and reused.

5.1.8 Pulp manufacturing process

This third system-specific analysis investigates the consequences of changing the pulping process on virgin paper towel GWP. While the kraft or sulfate pulping process is the most common, it represents only one of many technologies used to manufacture pulp. Other pulping processes include the sulfite pulping process, stone groundwood pulping, thermo-mechanical pulping, and chemi-thermomechanical pulping. Additionally, sulfate pulp can come either unbleached or bleached, with the ECF (elemental chlorine-free) method accounting for over half the production of bleached sulfate pulp [32, 52] (TCF or total chlorine-free is the other option). All these processes are evaluated for virgin paper towels, although not all are necessarily appropriate for tissue production; additional details for each of these processes can be found in [33].

Figure 28 illustrates the consequences of substituting alternative pulping processes on the GWP of virgin paper towels. The results vary from 3.5% below the baseline (unbleached sulfate pulp) to 9.8% above the baseline (chemi-thermomechanical).

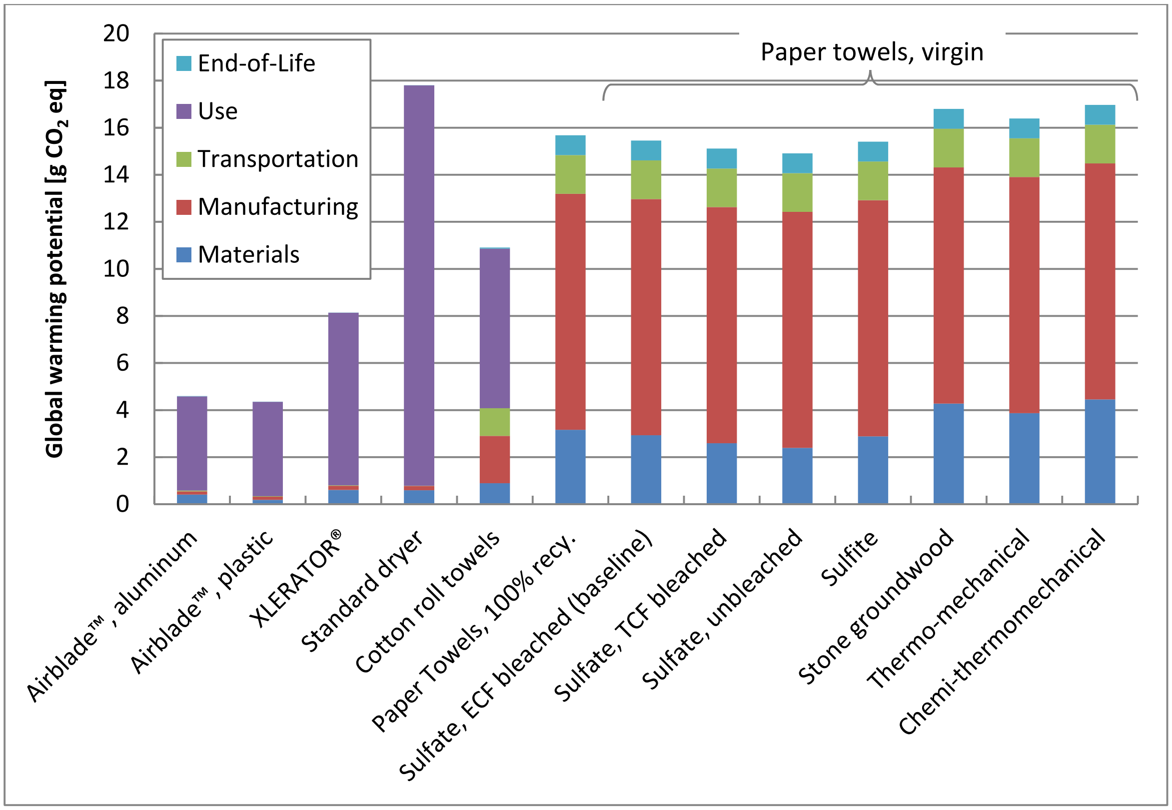


Figure 28 Effect of pulping process on virgin paper towel GWP.

5.1.9 Paper towel mass

In addition to paper towel use intensity, paper towel mass can also affect drying system environmental impact. This study assumed a paper towel use intensity of two towels per hand drying based on observations from a University of Florida study [37]—and assumption consistent with the other LCA studies reviewed in this report (only the Kimberly-Clark study assumes a lower use intensity of 1.5 towels per hand drying [13]). Paper towel mass, however, varied widely between LCA studies, from 1.98 g for Kimberly-Clark and Excel [13, 14], to 4 g for ETSA [12] (see Table 40). The consequences of changing paper towel mass are illustrated in Figure 29. Environmental impact calculations continue to assume a 3.85% manufacturing loss, consistent with baseline assumptions, and that two paper towels are used per hand dry.

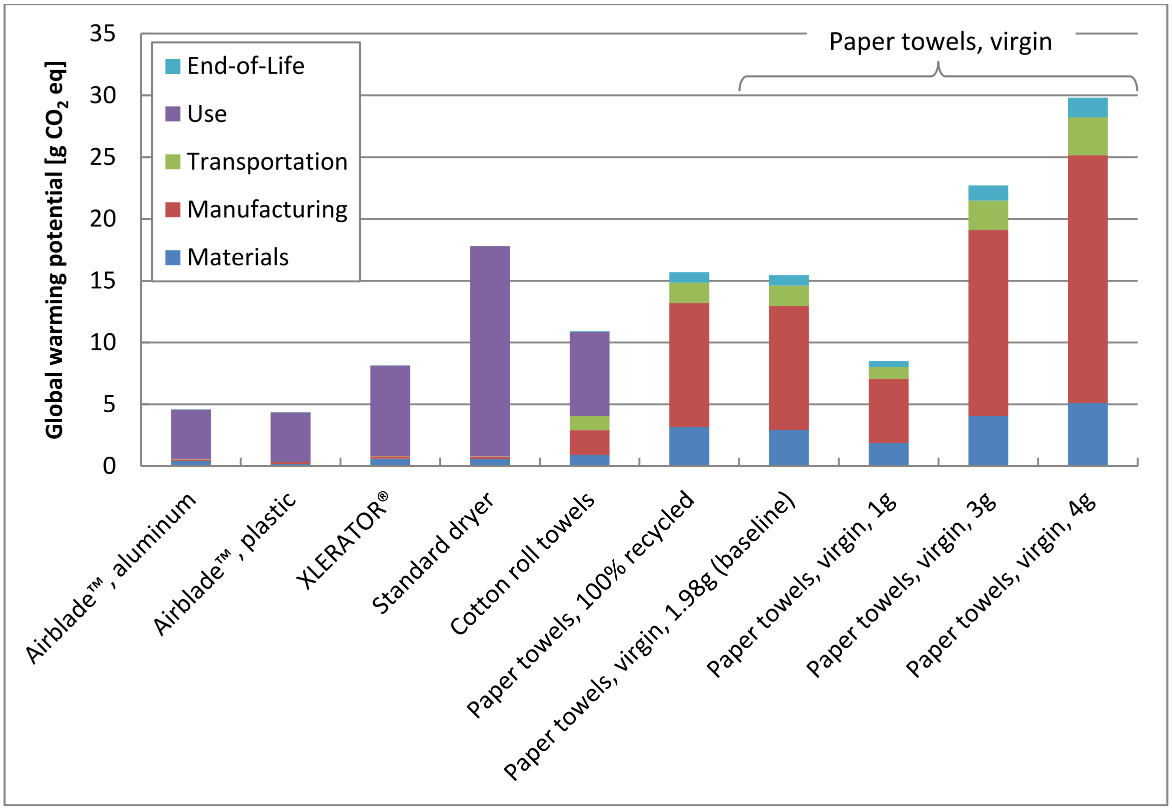


Figure 29 Effect of paper towel mass on virgin paper towel GWP.

5.1.10 Allocation of recycled content

The third paper towel sensitivity analysis investigates how changing the allocation of the burden from recycled content can affect paper towel GWP. In allocation for an open-loop recycling system, a methodological decision has to be made regarding which product within the system receives the burden for primary material production (in this case, pulp production from wood), recycling (i.e. re-pulping from waste paper), and end-of-life; burdens from manufacturing and transportation are assigned to their respective products. Since multiple product life cycles are involved, a product's burden also depends on whether it can use recycled content and whether it can be recycled. For instance, paper towels can use recycled content, but cannot be recycled [13] and therefore represent the final product before disposal. A description of the different allocation schemes used in this analysis is included in Appendix A.4. The cut-off scheme, in which the full re-pulping and end-of-life impacts are assigned to the paper towels, is chosen for the baseline scenario. No allocation is necessary for virgin paper towels: they cannot be recycled and thus are allocated the full burdens of pulp production and end-of-life.

Impact results are shown in Figure 30 for paper towels manufactured entirely from recycled content. Depending on allocation choice, the burden of paper towels from recycled content can be more or less than the burden of towels manufactured from virgin content. Ultimately, changing the allocation scheme does not change whether paper towels are preferred over cotton roll towels or high-speed hand dryers as the majority of a paper towel's burden comes from tissue manufacturing, which is unaffected by allocation choice.

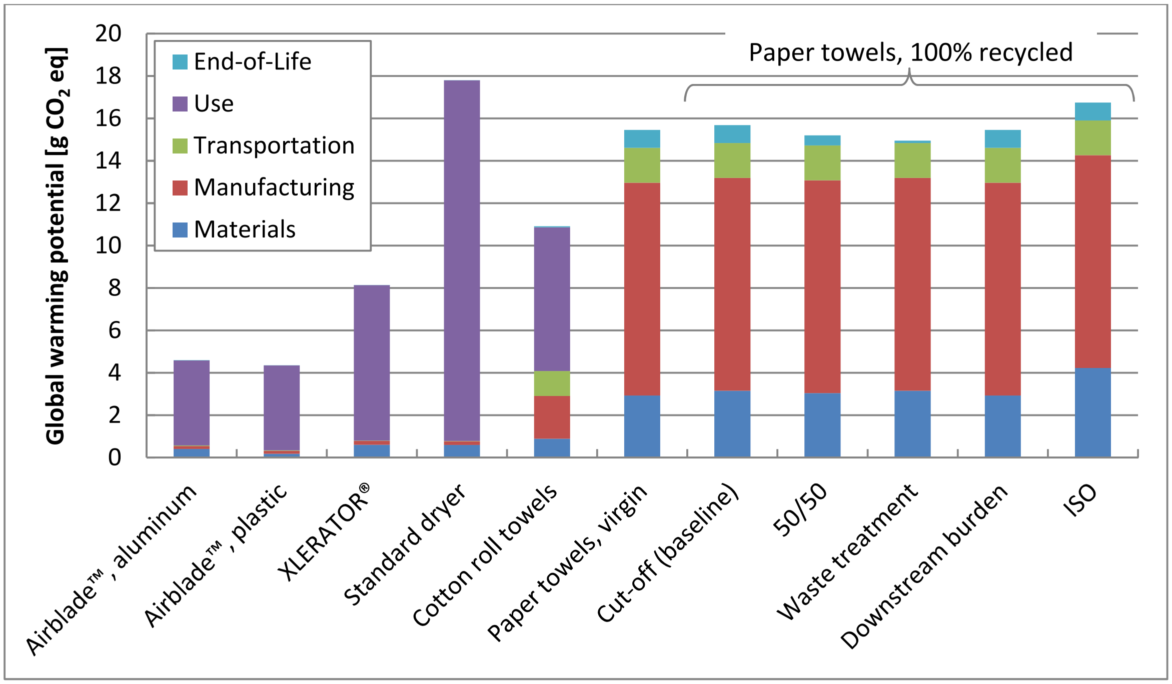


Figure 30 Effect of different allocation schemes for recycled content on paper towel GWP.

5.1.11 Manufacturing location

The next two analyses investigate drying system GWP sensitivity to manufacturing and use locations. The manufacturing location analysis differs from the analysis concerning manufacturing stage grid mix because it affects not only grid mix, but also transportation distance to warehouse (which is not accounted for in Section 5.1.2). In the baseline scenario, dryers and cotton roll towels are assumed to be manufactured in China, while paper towels are manufactured in the US—the same location where they are used. The sensitivity analysis considers two alternative manufacturing locations: Malaysia, where Dyson Airblade™ hand dryers are manufactured, and the US, where XLERATOR® dryers are manufactured. The GWPs of all products, with the exception of paper towels, are evaluated assuming the products were manufactured in the alternative locations; paper towel manufacturing is assumed to continue to take place in the States because the use location is unaffected.

Table 11 summarizes the changes in analysis parameters; impact results are shown in Figure 31. Because production and transportation comprise a small fraction of overall impact for the hand dryer systems (see Figure 5), the GWPs of these systems are relatively unaffected by the change in manufacturing location. Altering manufacturing location has a slightly larger effect on the cotton roll towel system GWP as production and transportation account for over 40% of its overall GWP. The paper towel systems are also affected because the dispenser, waste bin, and bin liners are assumed to be manufactured in the US or Malaysia as opposed to China; the impact attributable to the paper towels, however, is unchanged.

Table 11 Manufacturing location assumptions.

Manufacturing location	China (baseline)	US	Malaysia	Ref
Manufacturing grid mix	CN avg.	US avg.	MY avg.	
Coal	78.6%	49.3%	26.9%	[32, 53]
Natural gas	0.32%	17.4%	63.6%	
Nuclear	2.1%	19.6%	0%	
Renewable[a]	16.1%	8.9%	7.7%	
Transportation				
Raw material to plant	250 km	250 km	250 km	[27, 43, 44]
Port A to B	10,500 km	0 km	15,160 km	
Port B to warehouse	2,624 km	0 km	2,624 km	

(a) Renewable includes electricity produced from hydropower, solar, wind, and cogen

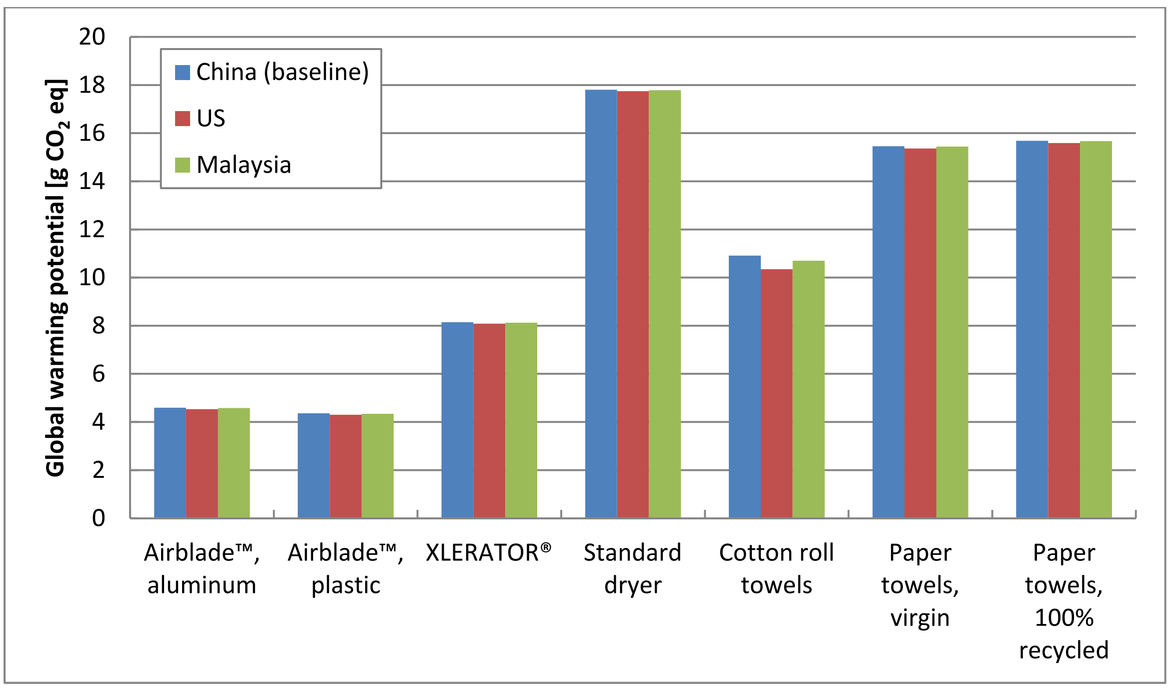


Figure 31 Effect of altering manufacturing location on drying system GWP.

5.1.12 Use location (regional variation)

This sensitivity analysis investigates how hand-drying system impact changes with use location. Altering use location affects not only the transportation required to deliver the product from its manufacturing plant in China to the new location, but also the electric grid mix, use intensity, and the end-of-life scenario. Paper towel manufacturing location is also impacted because towels are assumed to be manufactured in the same country where they are used.

Theoretically, the impact of regional variation can be estimated from the previous sensitivity analyses since emissions from a region's grid will likely fall between the emissions of the hypothetical all-coal and all-hydropower grids (Section 5.1.2). Likewise, the average use intensity associated with a region can reasonably be expected to be similar to the ranges considered in Section 5.1.4. Transportation is not anticipated to have a significant impact on GWP because it accounts for a small fraction of overall impact (see Figure 5). Changing the end-of-life scenario is also likely to have minimal effect on GWP (see Section 5.1.5). Similar assumptions as those used by the baseline scenario are applied: landfill methane emissions are captured and flared with energy recovery, and only cardboard packaging is recycled (although the latter is not strictly true in Europe because of the waste electrical and electronic equipment directive [39]). Whether or not energy recovery takes place from incineration depends on the country. Nonetheless, it is worthwhile to conduct this analysis and compare hand-drying system impact outside the US. Table 12 summarizes assumptions for four locations: US (baseline), France, Germany, and UK; secondary regions are included in Appendix A.7.2.

Table 12 Regional assumptions.

Use location	US	France	Germany	UK	Ref
Transportation					
Port A to B	10,500 km	19,625 km	19,625 km	19,100 km	[27, 43, 44]
Port B to warehouse	2,624 km	30 km	30 km	372 km	
Warehouse to washroom	1,760 km	644 km	752 km	541 km	
Grid mix	US avg.	FR avg.	DE avg.	GB avg.	
Coal	49.3%	4.4%	44.0%	32.6%	[32]
Natural gas	17.4%	3.6%	10.6%	40.9%	
Nuclear	19.6%	76.8%	25.3%	19.1%	
Renewable[a]	8.9%	12.1%	9.7%	3.4%	
Use intensity[b]					
Airblade™	12 sec	10 sec	10 sec	10 sec	[12, 14, 27]
XLERATOR®	20 sec	18 sec	18 sec	18 sec	
Standard dryer	31 sec	28 sec	28 sec	29 sec	
Cotton roll towels	1 towel	1 towel	1 towel	1 towel	
Paper towels	2 towels	2 towels	2 towels	2 towels	
Dryer power rating					
Airblade™	1,400 W	1,600 W	1,600 W	1,600 W	[27]
XLERATOR®	1,500 W	1,400 W	1,400 W	1,400 W	
Standard dryer	2,300 W	2,400 W	2,400 W	2,400 W	
MSW					
Cardboard recycled	76.6%	60%	70%	45%	[30, 54]
Incinerated	0%	7%	12%	3%	
Incinerated w/ recovery	19%	9%	21%	0%	
Landfilled	81%	84%	67%	97%	

(a) Renewable includes electricity produced from hydropower, solar, wind, and cogen

(b) Dryer use intensity measured according to NSF Protocol P335 [19].

Impact results are shown in Figure 32. For dryers, the electric grid mix has the largest effect on GWP—consistent with observations in Section 4.2. Dryers in the US, Germany, and the UK all rely on coal- and gas-intensive grids and thus have larger GWPs than dryers in France, where nuclear power supplies the majority of the electricity. This difference in grid mix has a smaller effect on towel system GWPs because a large fraction of their burdens are derived from natural gas rather than electricity.

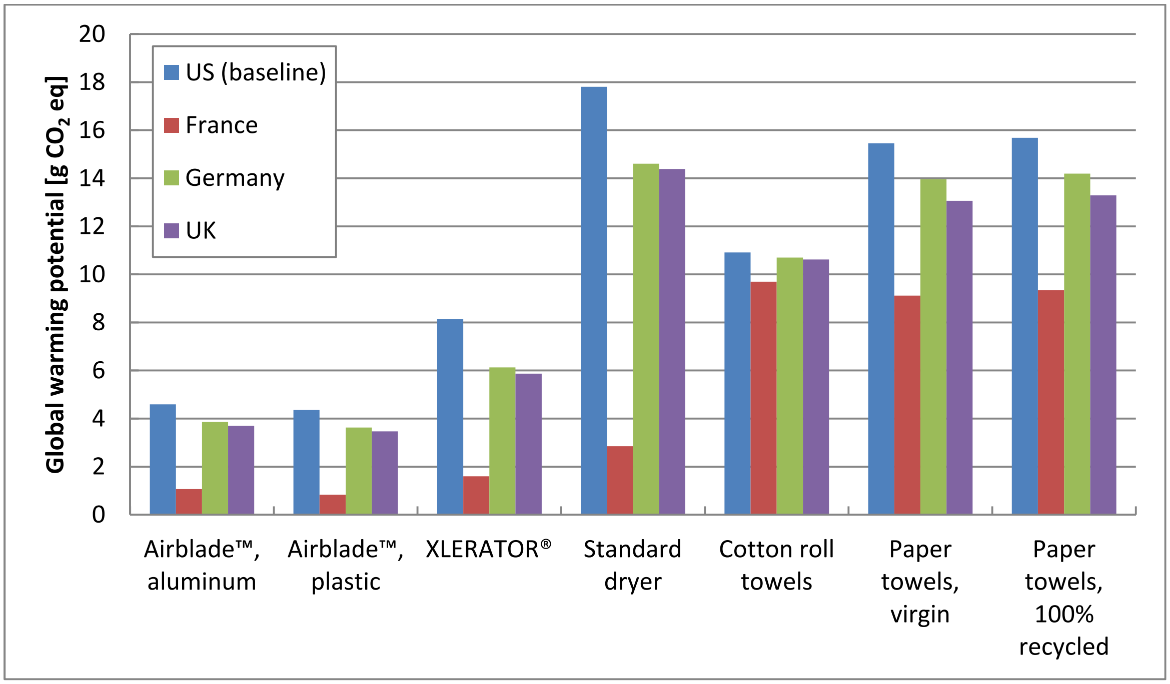


Figure 32 Effect of regional variation on drying system GWP.

5.2 Uncertainty analyses

Two analyses are conducted to evaluate how drying system environmental impact is affected by uncertainty and variation in life cycle inventory flows. The first of these investigates variation in the assumptions that define the baseline scenario and the second addresses uncertainty and variation in the bill of activities data.

5.2.1 Scenario uncertainty

Investigating variation in the baseline scenario assumptions is necessary because, while the sensitivity analyses (Section 5.1) provide some insight into the effect of this variation on drying system GWP, there remains a gap in understanding because most of the analyses conducted vary only one parameter at a time. Consequently, they cannot address how interactions between these parameters might affect system GWP. Even the manufacturing location and regional variation analyses, which combine multiple parameters, consider only a limited set of scenarios. A scenario uncertainty analysis is therefore used to explore the potential impacts of multiple parameters varying simultaneously, thereby simulating a range of scenarios. The analysis is essentially a test of the choices made in framing the life cycle assessment.

In this scenario uncertainty analysis, the Monte Carlo method is used to randomly sample values for a set of drying system parameters, such as use intensity or electric grid mix; the set of parameters characterize a scenario. Environmental impact is then calculated based on the selected parameter values. The analysis is implemented in Excel with Crystal Ball and uses data obtained from ecoinvent via SimaPro.

Table 13 summarizes the independent parameters considered in the uncertainty analysis. A uniform distribution is assumed for all the parameters due to lack of information on actual distributions. The first five parameters in the table concern lifetime usage, which is represented as the number of pairs of hands dried before the product is disposed. These parameters are uncorrelated in this uncertainty analysis because there is no reason to expect a standard dryer will last as long as an XLERATOR® dryer or vice versa. Thus, five independent variables are used in the analysis, one for each dryer system, plus two more for the towel dispensers and waste bin. The number of times the cotton towel itself can be laundered and reused is also included in the analysis.

The next set of parameters concern manufacturing and use phase electric grid mixes. Manufacturing grid mixes are assumed to be independent (i.e. uncorrelated) for each drying system because there is no reason to expect that products will be manufactured in the same region. Use grid mixes, however, are perfectly correlated across the systems because the systems' use phases take place in the same washroom (or at most 100-km away, as is the case for cotton roll towel laundering). Keeping dryers and cotton roll towels on the same grid also ensures a consistent comparative basis for the use phase.

The uncertainty analysis represents grid mix as a continuous variable of kg CO_2 eq per kWh; it is not necessary to define the exact fractions of coal, natural gas, hydropower, etc. required to generate that kilowatt-hour of electricity because only the grid's GWP matters in the calculations. The minimum and maximum values for the grid mix parameters are estimated based on the GWPs of the hypothetical all-hydropower and all-coal grids (same as those used in Sections 5.1.2 and 5.1.3).

Drying system use intensity is decoupled for dryers and towels under the assumption that the average user treats hand dryers, cotton roll towels, and paper towels differently. For instance, a user who only spends a few seconds in front of a hand dryer may nonetheless grab three paper towels to dry his hands quickly. Towel usage is assumed to vary continuously between one and two cotton roll towel pulls or between one and three paper towels. Two sets of dry times are defined for dryer use intensity—as introduced in Section 3.1.2. The first represents drying-driven usage in which users hold their hands in the air stream until a desired dryness is achieved. The dry time ranges for this drying-driven usage pattern are defined as 50% below to 25% above measured baseline dry times (as defined by the NSF Protocol P335 in Table 4). The second set of dry time ranges represents time-driven usage, in which users wait the same length of time for their hands to dry, regardless of dryer type, before leaving. Parameter limits for this time-driven usage pattern are approximated to represent the range of "reasonable" drying-driven usage times. A lower limit of 5 seconds was chosen based on the Dyson Airblade™ hand dryer's minimum dry time in the drying-driven scenario, and an upper limit of 30 seconds as the maximum time users are likely to wait for their hands to dry. In both cases, dry times are perfectly correlated across dryers.

Table 13 Parameter ranges and distributions in Monte Carlo simulation.

Independent parameters	Drying systems	Baseline	Range	Distribution
Lifetime usage	Airblade™	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Lifetime usage	XLERATOR®	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Lifetime usage	Standard dryer	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Lifetime usage	Cotton roll towel (dispenser)	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Lifetime usage	Paper towel (dispenser and bin)	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Number of reuses	Cotton roll towel	103	70 – 130 launderings and reuses	Uniform
Manufacturing grid mix	Airblade™	CN average	0.019 – 1.44 kg CO_2 eq / kWh	Uniform
Manufacturing grid mix	XLERATOR®	CN average	0.019 – 1.44 kg CO_2 eq / kWh	Uniform
Manufacturing grid mix	Standard dryer	CN average	0.019 – 1.44 kg CO_2 eq / kWh	Uniform
Manufacturing grid mix	Cotton roll towels	CN average	0.019 – 1.44 kg CO_2 eq / kWh	Uniform
Manufacturing grid mix	Paper towels	US average	0.011 – 1.22 kg CO_2 eq / kWh	Uniform
Use grid mix	Airblade™ XLERATOR® Standard dryer Cotton roll towels	US average	0.016 – 1.32 kg CO_2 eq / kWh	Uniform
Use intensity	Airblade™ XLERATOR® Standard dryer	12 seconds 20 seconds 31 seconds	*Drying-driven:* -50% to +25% of measured baseline; *Time-driven:* 5 – 30 seconds	Uniform
Use intensity	Cotton roll towels	1 towel	1 – 2 towels	Uniform
Use intensity	Paper towels	2 towels	1 – 3 towels	Uniform
MSW incineration fraction	All	19%	0% – 100%	Uniform
Compost	Paper towels, Cotton roll towels	N	Y, N	Binary

The last two parameters in Table 13 concern the end-of-life stage. The first, municipal solid waste (MSW) incineration fraction, applies to all hand-drying systems and specifies the percent of each system that is incinerated after disposal (the remainder is assumed to be sent to a landfill). While applying the same scenario to both dryers and paper towels may not be wholly realistic given that dryers are disposed after a life span of five years whereas paper towels are disposed only after a single use, the incineration fraction is not anticipated to change within so short a time frame. As a case in point, the fraction of US waste incinerated after recovery for recycling has changed very little since 1990 when the US incinerated around 17.2% of its waste [30]. Finally, composting indicates whether the towels are composted or incinerated and/or sent to a landfill.

Parameters not listed in Table 13 are assumed to be the same as in the baseline scenario. For example, ECF-bleached sulfate pulp is assumed for paper towels manufactured from virgin content, and the cut-off strategy for allocating recycled content assumed for paper towels containing such content.

The resulting GWP probability distributions after 20,000 iterations are presented in Figure 33 for both drying-driven (Figure 33a) and time-driven (Figure 33b) usage patterns. Statistics for the distributions are detailed in Table 14. Only five of the seven systems are shown: analyses for the plastic Dyson Airblade™ hand dryer and paper towels manufactured with recycled content were not conducted due to the similarity of the baseline results for these products with the aluminum Dyson Airblade™ hand dryer and the paper towels made form virgin pulp, respectively. Dryer GWP distributions associated with time-driven usage are similar because the dryers themselves are differentiated only by their respective power ratings: dry times are the same for all dryers. By contrast, the distributions of the XLERATOR® and standard dryer systems have a much wider spread than that of the Dyson Airblade™ hand dryer system when drying-driven usage is considered. This is due to the broader range of dry times for the first two systems: since drying-driven usage varies from -50% to +25% of the measured baseline, the XLERATOR® and standard dryer dry times have a wider spread (10 to 25 seconds and 16 to 39 seconds, respectively) owing to their longer measured dry times relative to that of the Dyson Airblade™ hand dryer (see Table 4).

While the probability distributions of drying system GWP in Figure 33 clearly overlap, these curves are not indicative of the relative impacts for any given scenario from the Monte Carlo simulation because they are not fully independent of each other. Comparison indicators (CI), as proposed by Huijbregts [55], are therefore used to estimate the frequency with which the impact of one drying system is lower than that of another for a given scenario. Following this approach, two drying systems are compared by calculating the ratio—the comparison indicator—of their environmental impacts for each iteration in the Monte Carlo analysis. If the resulting distribution of this ratio is consistently above or below one, then it is possible to claim that the impact of one drying system is consistently higher than the impact of another. However, if the distribution falls around one, then it is not possible to make such a claim, because it indicates that there are numerous scenarios where the rank order of impact among the products is switched.

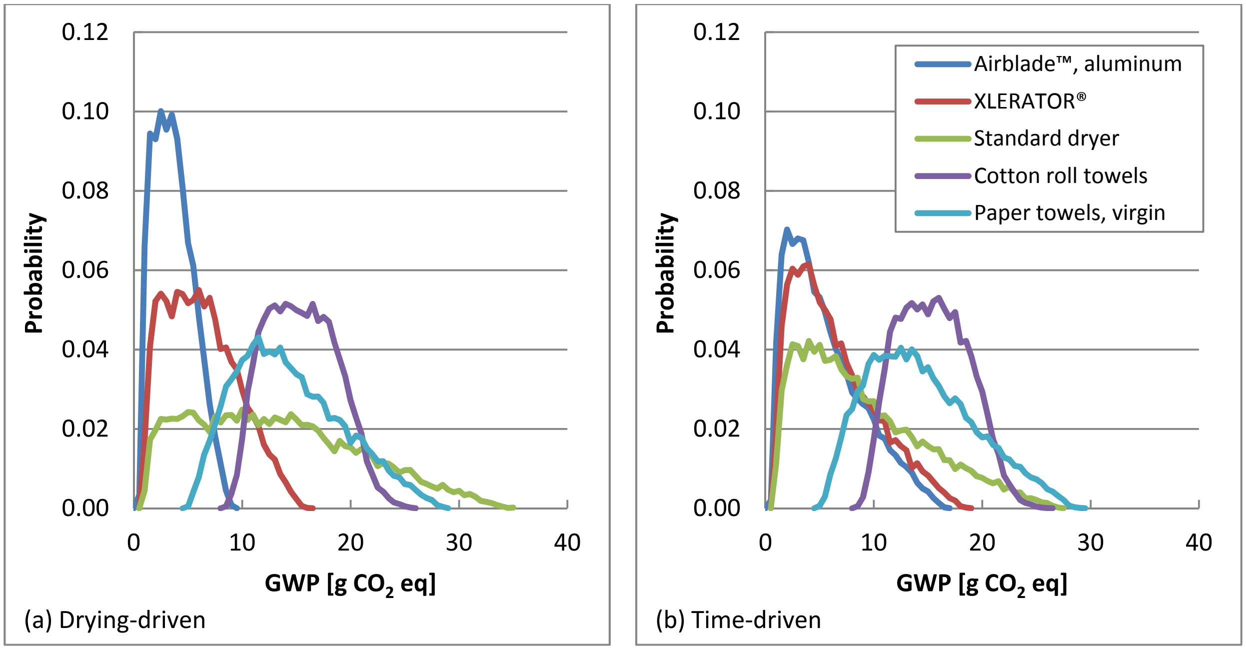


Figure 33 GWP probability distributions given (a) drying-driven and (b) time-driven usage patterns.

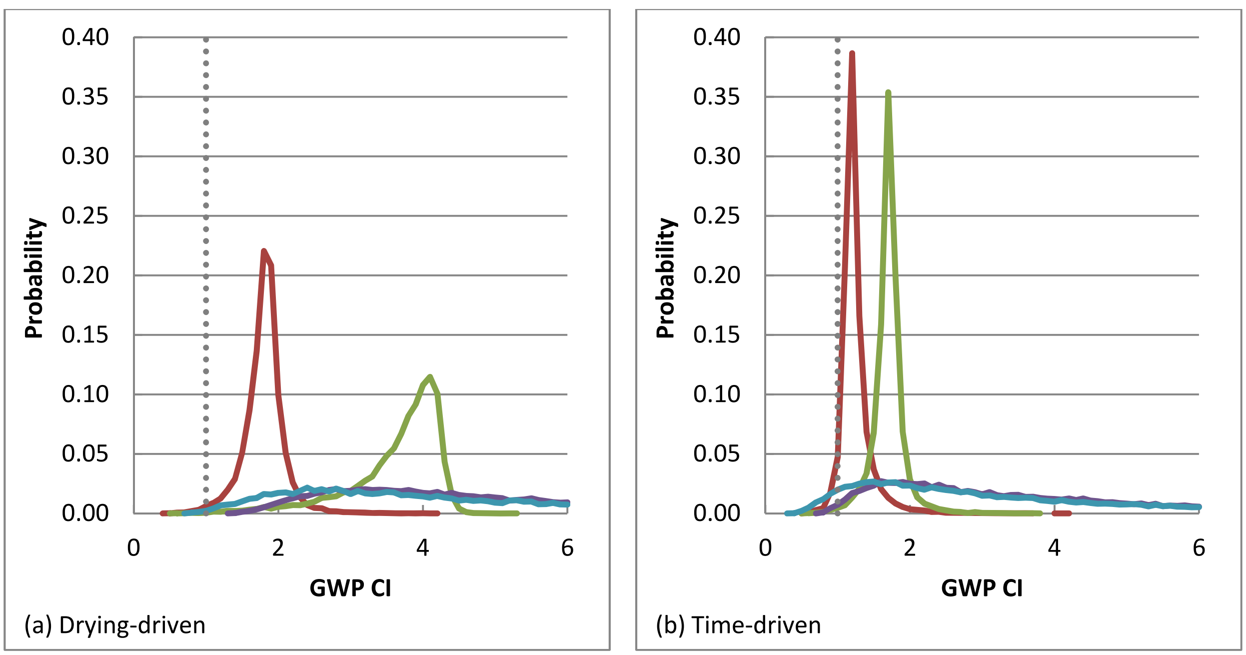


Figure 34 GWP comparison indicator probability distributions (calculated relative to Airblade GWP).

Table 14 Statistics for GWP distributions in Figure 33 (in units of g CO_2 eq).

	Mean	Median	St. Dev.	COV*	Min	Max	Baseline
Drying-driven							
Airblade™, aluminum	3.42	3.23	1.79	0.52	0.36	8.83	4.59
XLERATOR®	6.02	5.71	3.25	0.54	0.55	15.8	8.14
Standard dryer	12.9	12.2	7.58	0.59	0.63	34.9	17.8
Cotton roll towels	15.2	15.1	3.21	0.21	8.11	25.5	10.9
Paper towels, virgin	14.1	13.4	4.86	0.34	4.78	28.4	15.5
Time-driven							
Airblade™, aluminum	5.28	4.53	3.41	0.65	0.38	16.2	4.59
XLERATOR®	6.07	5.27	3.75	0.62	0.54	18.4	8.14
Standard dryer	8.72	7.48	5.68	0.65	0.59	26.8	17.8
Cotton roll towels	15.3	15.2	3.20	0.21	8.16	25.8	10.9
Paper towels, virgin	14.2	13.5	4.89	0.35	4.81	28.6	15.5

*COV: coefficient of variation = standard deviation/mean

Comparison indicator distributions for the GWP of different drying systems relative to that of the aluminum Dyson Airblade™ hand dryer are shown in Figure 34 given both drying-driven and time-driven usage patterns. The results indicate that for drying-driven dry times, the comparison indicator distribution is almost entirely above one. By contrast, this distribution is shifted to the left for time-driven dry times. This shift to the left is reflected in Table 15, which shows the frequency at which the GWP of the Dyson Airblade™ hand dryer system is higher than that of the other drying systems given both drying-driven and time-driven dry times. Overall, however, the GWP of the Dyson Airblade™ hand dryer is still lower than that of any given drying system in over 92% of the iterations.

The results in Table 15 indicate that the Dyson Airblade™ hand dryer system almost always has the lower impact for a given scenario due to the correlation between use phase grid mix and between dryer use intensity parameters. Thus, when the Dyson Airblade™ hand dryer is operated on a carbon-intensive grid, so too are the XLERATOR® and standard dryers; likewise, when the Dyson Airblade™ hand dryer is used at low intensity, the other dryers are as well, leading the Airblade™ to be consistently favored as it has the shorter dry time (in the case of drying-driven usage) and the lower power rating. There are a few instances, however, when the XLERATOR® system has the lower impact. This occurs in scenarios where the XLERATOR® dryer has a high lifetime usage, the Dyson Airblade™ hand dryer a low lifetime usage, and the use phase a low-carbon grid mix. The greener use phase grid mix reduces the use phase burden relative to the production phase burden so that the latter instead of the former drives dryer system impact. Since production impact determines rank order of drying systems, the XLERATOR® system is then favored over the Dyson Airblade™ hand dryer system because its higher lifetime usage enables the allocation of its production burden over more pairs of hands and reduces the impact associated with drying any one pair of hands. This frequency is higher for time-driven usage because

use phase burdens are nearly equal, which in turn increases the likelihood that the XLERATOR® GWP will be less than the GWP of the Dyson Airblade™ hand dryer—in the case of this analysis, 7.3% compared to 1.3% of Monte Carlo iterations for time- and drying-driven usage, respectively. The longer Dyson Airblade™ hand dryer dry times associated with time-based usage also increase the frequency at which the paper towel system will have a lower impact than the Dyson Airblade™ hand dryer system.

Table 15 Comparison indicator frequencies.

		Frequency $GWP_A < GWP_B$	
Drying system A	**Drying system B**	**Drying-driven**	**Time-driven**
XLERATOR®	Airblade™, aluminum	1.3%	7.3%
Standard dryer	Airblade™, aluminum	0.16%	0.95%
Cotton roll towels	Airblade™, aluminum	0.0%	1.3%
Paper towels, virgin	Airblade™, aluminum	0.40%	6.5%

Additional scenario uncertainty results indicate that the variation in dryer system GWP is primarily driven by the variation in use stage grid mix, followed by dryer use intensity. By contrast, the variation in cotton roll towel system GWP is due to changes in towel use intensity and then to changes in manufacturing- and use-stage grid mix. For the paper towel systems, variation in the towel use intensity and in the manufacturing stage grid mix matter the most.

The current scenario uncertainty analysis assumes that regardless of usage pattern, use intensity is perfectly correlated among the hand dryers. In reality, this may not be the case as the dryers are inherently different and may elicit different user behavior. Additionally, the current analysis defaults to the baseline scenario for all assumptions and parameters not listed in Table 13. The contribution and sensitivity analyses (Sections 4.4 and 5.1), however, show that altering some of these assumptions reduces drying system GWP. In particular, the choice of unit process for the XLERATOR® and standard dryer control and optics assemblies (Section 5.1.6) is addressed.

Global warming potential and comparison indicators are therefore reevaluated under different sets of assumptions for both drying-driven and time-drive usage patterns. The first reevaluation assumes uncorrelated dryer use intensity, but is otherwise the same as the original scenario uncertainty analysis. The second not only assumes uncorrelated dryer use intensity, but also replaces the unit process for the XLERATOR® and standard dryer control and optics assemblies with the lower-impact printed wiring board (PWB) process.

Comparison indicators for each set of assumptions are summarized in Table 16, which includes the results from Table 15. The results indicate that removing the correlation between dryer use intensities increases the frequency at which the GWPs of the XLERATOR® and standard dryer systems are less than that of the Dyson Airblade™ hand dryer system, particularly for time-driven usage. The comparison indicators for cotton roll towel and paper towel systems are unaffected. Changing the electronics unit process for the XLERATOR® and the standard dryers also increases the number of Monte Carlo-generated scenarios that result in their GWPs undercutting the Dyson Airblade™ hand dryer GWP. For the XLERATOR® system, use of the PWB unit process reduces GWP enough so that half the time, its impact is less than that of the Dyson Airblade™ hand dryer system when time-driven usage is assumed.

Table 16 Summary of comparison indicators from scenario uncertainty analyses.

Usage pattern	Dryer use intensity correlated?	XLERATOR® and Std. dryer electronics	Frequency $GWP_X < GWP_{Airblade™}$			
			XLERATOR	Std. dryer	Cotton towels	Paper towels
Drying-driven	Y	Electronic component	1.3%	0.16%	0.0%	0.40%
Drying-driven	N	Electronic component	4.5%	0.15%	0.0%	0.45%
Drying-driven	N	PWB	14%	1.2%	0.0%	0.44%
Time-driven	Y	Electronic component	7.3%	0.95%	1.3%	6.5%
Time-driven	N	Electronic component	37%	19%	1.3%	6.2%
Time-driven	N	PWB	50%	27%	1.3%	6.4%

5.2.2 Bill of activities uncertainty analysis

In addition to assessing scenario uncertainty, it is also useful to investigate uncertainty and variation in the bill of activities data—that is, the amount of materials, processing, energy, and transport required over the life cycle of a product system. Thus, this analysis evaluates uncertainty in quantities of all unit processes listed in the bill of activities and their effect on drying system environmental impact. Often, however, such uncertainty data are not available and somehow have to be estimated. This estimation is conducted with a pedigree matrix approach, described in [32], which is used to qualitatively assess data source quality and to quantify the uncertainty that poor quality sources may introduce into the life cycle assessment. The same methodology is used by ecoinvent to assess the quality of their own data sources for all unit processes in their database.

Table 39 in the appendix details the quality levels and resulting geometric standard deviations for each unit process used in this analysis. All processes are assumed to follow a lognormal distribution based on observations by Hofstetter [56] and the fact that it is the primary distribution used by ecoinvent [32]. Once distributions have been defined for all unit processes and entered into SimaPro, a Monte Carlo simulation is run for 500 iterations. By default, SimaPro assumes unit processes that appear multiple times within a drying system's inventory are correlated [57]; drying systems, however, are analyzed independently.

The resulting GWP distributions can be used to assess the consequences of data source quality on drying system environmental impact. Specifically, the distributions are compared with a t-test to determine whether differences between their means are statistically significant. In this case, t-test determines whether impact of drying system A is lower than that of drying system B. Whether the distributions pass or fail the test depends on the significance level, α, which represents the probability of stating that the impact of drying system A is lower than that of drying system B when, in fact, their distributions and means are statistically indistinguishable. Typically α is chosen to be equal to or less than 0.05—thus, a 5% chance that the statement that drying system A has the lower impact is incorrect—for statistical significance.

Since t-tests require that each sample be normally distributed, a chi-square goodness of fit test is used to determine whether the normal or lognormal models are appropriate representations of GWP distributions. Additional details can be found in Appendix A.3.1.

Table 17 Statistics for inventory uncertainty analysis from Figure 35 (in units of g CO_2 eq).

Drying system	Mean	Median	St. Dev.	COV*	Min	Max	Baseline
Baseline scenario (measured dry times)							
Airblade™, aluminum	4.62	4.36	1.62	0.351	2.14	17.8	4.59
XLERATOR®	8.0	7.55	2.68	0.335	3.07	20.9	8.14
Standard dryer	17.9	16.8	6.41	0.358	6.60	65.4	17.8
Cotton roll towels	11.0	10.9	1.29	0.117	7.54	16.6	10.9
Paper towels, virgin	15.4	15.2	2.06	0.134	10.6	21.9	15.5
Baseline scenario (reported dry times)							
Airblade™, aluminum	4.62	4.36	1.62	0.351	2.14	17.8	4.59
XLERATOR®	5.51	5.19	1.80	0.327	2.29	14.9	5.35
Standard dryer	17.5	16.3	6.32	0.361	6.02	46.6	17.3
Cotton roll towels	11.0	10.9	1.29	0.117	7.54	16.6	10.9
Paper towels, virgin	15.4	15.2	2.06	0.134	10.6	21.9	15.5
PWB unit process substituted in XLERATOR® and standard dryer inventories (reported dry times)							
Airblade™, aluminum	4.62	4.36	1.62	0.351	2.14	17.8	4.59
XLERATOR®	4.80	4.47	1.86	0.387	1.80	14.9	4.87
Standard dryer	17.0	15.9	5.92	0.348	5.29	43.7	16.8
Cotton roll towels	11.0	10.9	1.29	0.117	7.54	16.6	10.9
Paper towels, virgin	15.4	15.2	2.06	0.134	10.6	21.9	15.5

*COV: coefficient of variation = standard deviation/mean

Monte Carlo simulations are run in SimaPro for each drying system under three sets of conditions: 1) baseline scenario assumptions given measured dry times (see Table 4); 2) baseline scenario assumptions given reported dry times; and 3) baseline scenario assumptions given reported dry times, but with the PWB unit process used for the XLERATOR® and standard dryer control and optics assemblies. GWP distribution results for the first baseline scenario with measured dry times are shown in Figure 35 with statistics detailed in Table 17. Since chi-square goodness of fit test results indicated that the lognormal model is a reasonable fit for all distributions, the distributions were transformed to normal and compared via the t-test. T-test results are shown in Table 18 for $\alpha = 0.01$; additional information is included in Appendix A.3.1.

In most cases, it is possible to state that the distributions are statistically different and identify which is associated with the lower mean impact. One of the two exceptions is the comparison between the standard dryer and the paper towel distributions, which fails the t-test in the baseline case with reported dry times and in the case with reported dry times, plus the use of the printed wiring board (i.e. non-generic) unit process for the standard dryer's control and optics assemblies. In the latter case, the distributions are still indistinguishable even when the criterion for statistical significance is relaxed to $\alpha = 0.05$. Using the standard dryer's measured dry time, however, increases the dryer system's impact enough that the difference between it and the paper towel system becomes statistically significant. The second exception is the comparison between the aluminum Dyson Airblade™ hand dryer and the XLERATOR® dryer when the GWPs are calculated with reported dry times and the printed wiring board unit process for the XLERATOR®'s optics and control assemblies. Under these conditions, the XLERATOR®'s GWP is reduced compared to the baselines making the two dryer distributions statistically indistinguishable at both a 1% and a 5% significance level.

Table 18 Drying system t-test results after lognormal to normal transformation.

Drying system A	Drying system B	$GWP_A < GWP_B$ or indistinguishable at $\alpha = 0.01$?		
		Baseline, measured	Baseline, reported	PWB, reported
Airblade™, aluminum	XLERATOR®	Yes	Yes	Indistinguishable
Airblade™, aluminum	Standard dryer	Yes	Yes	Yes
Airblade™, aluminum	Cotton roll towels	Yes	Yes	Yes
Airblade™, aluminum	Paper towels, virgin	Yes	Yes	Yes
XLERATOR®	Standard dryer	Yes	Yes	Yes
XLERATOR®	Cotton roll towels	Yes	Yes	Yes
XLERATOR®	Paper towels, virgin	Yes	Yes	Yes
Cotton roll towels	Standard dryer	Yes	Yes	Yes
Cotton roll towels	Paper towels, virgin	Yes	Yes	Yes
Paper towels, virgin	Standard dryer	Yes	Indistinguishable	Indistinguishable

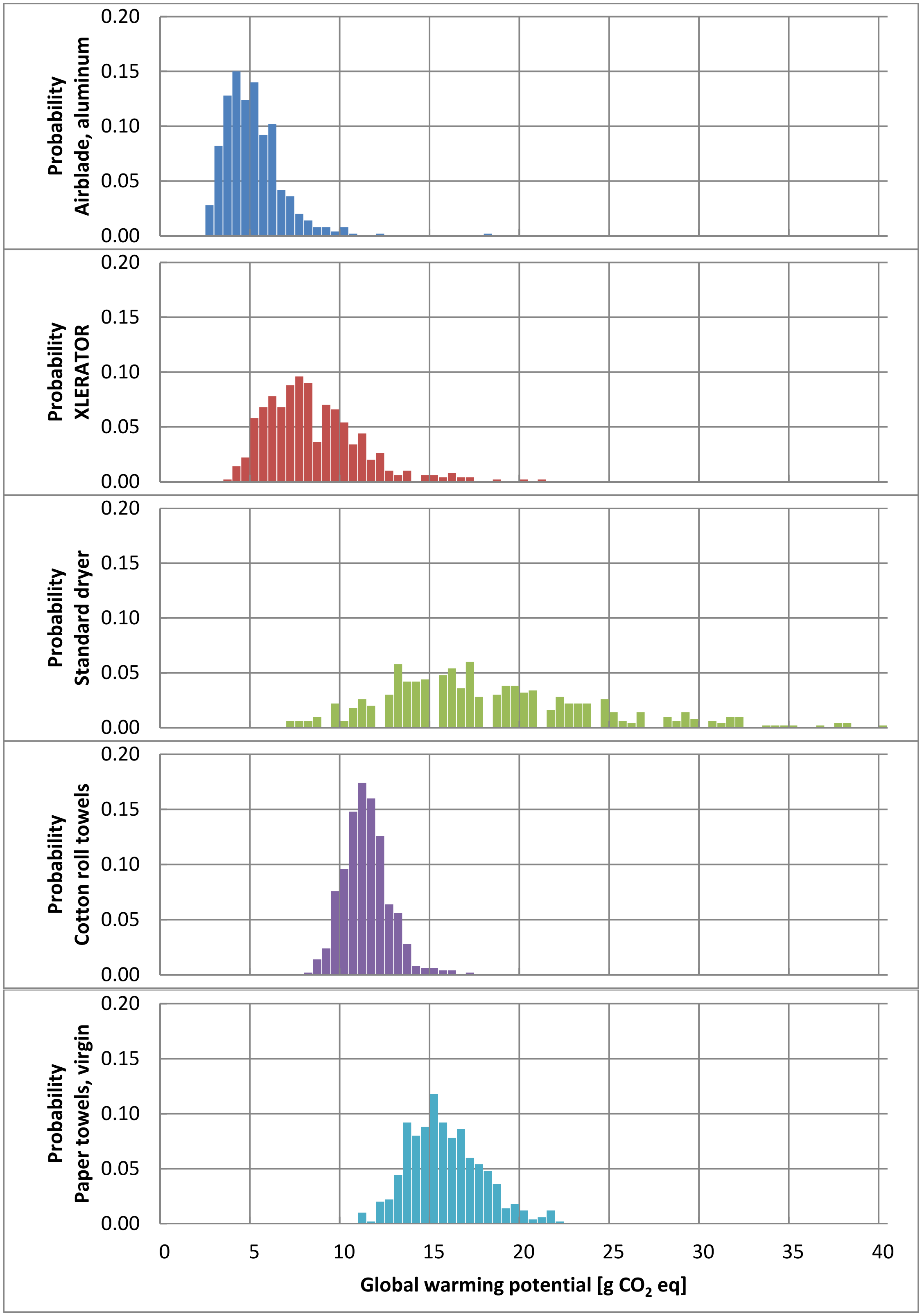


Figure 35 GWP probability distributions resulting from uncertainty in unit process inventory data. Assumes baseline scenario with measured dry times.

6 Conclusions

Baseline results in this study show that the environmental impact of high-speed hand dryers is generally lower than that of other hand-drying systems, although the exact rank order of the systems is sensitive to LCIA methodology (see Table 9). The Dyson Airblade™ hand dryer system, however, has the lowest impact regardless of impact assessment method. Even when scenario uncertainty is taken into account, the GWP of this drying system is nearly always the lowest, provided users follow the drying-based usage pattern and that hand dryer times are correlated (Table 15). It should be noted, however, that under time-based assumptions, the impact of the XLERATOR® dryer system is very close to that of Dyson Airblade™ hand dryer system.

Study results also indicate that the use stage is the primary driver of dryer system impact (Figures 5 – 9). Paper towel system impact, by contrast, is driven by the production stage and cotton roll towel system impact by both the production and use stages. Therefore, it is not surprising that electricity grid mix and use intensity have the largest influence on the GWP outcomes, as demonstrated in the sensitivity analysis (see Figures 21 – 23). These two parameters also contribute the most to variability in the scenario analysis.

The remainder of this section discusses these conclusions in more detail. Additionally, recommendations for reducing impact are listed in Section 6.4 and study limitations presented in Section 6.5. Completeness, sensitivity, and consistency checks are also included in Appendix A.8.

6.1 Key drivers of environmental impact

6.1.1 Hand dryers

The baseline results in Section 4.2.1 show that hand dryer environmental impact, regardless of impact assessment metric, is driven by the use phase energy consumed in the active use of the hand dryer (i.e., as opposed to stand-by or other modes—cf. Figure 15). The contribution analyses in Section 4.4 indicate that the key driver of impact within the production phase (including materials and manufacturing) depends on the product. For the aluminum Dyson Airblade™ hand dryer, production of the aluminum components represents over half of the burden, followed by the electricity used to assemble the product. Together they represent over 75% of the production GWP burden. By contrast, the production burden of the plastic Dyson Airblade™ hand dryer is dominated by the electricity used in assembly, followed by the production of the plastic components.

The GWP production burdens of the XLERATOR® and standard dryers are dominated either by the control and optics assembly or by the electricity used to assemble the product, depending on the inventory data used for the control and optics assembly. Regardless of drying system, the electricity associated with assembly is a significant fraction of the production burden.

6.1.2 Cotton roll towels

The key drivers of environmental impact for the cotton roll towels are more sensitive to the choice of impact assessment methodology. When global warming potential, human health, cumulative energy demand, and water consumption are used, the use phase (i.e., washing the towels) accounts for over half of the total impact, followed by transportation and manufacturing and then by materials. By contrast, the materials phase is much more significant in the ecosystem quality and land occupation metrics because they place greater emphasis on the burdens associated with growing the cotton compared to the other metrics. These results indicate that all life cycle phases, with the exception of end-of-life, are important to consider when assessing the life cycle impact of cotton roll towels.

The contribution analysis shows that between material production (cotton fibers) and processing (spinning, weaving, and de-sizing), no single step dominates the GWP production impact of a cotton towel roll. Furthermore, the analysis indicates that the use of natural gas in the washing step is the primary driver of GWP.

6.1.3 Paper towels

The key drivers of environmental impact for paper towels also depend on the impact assessment methodology. The manufacturing phase makes up over half of the impact for global warming potential and water consumption, followed by the materials production phase and transportation. It is noteworthy that paper towels are the only product for which product end-of-life has any significant impact—specifically in global warming potential (caused by degradation of paper towels in landfills). For the ecosystem quality and cumulative energy demand methods, the materials phase is the key driver, making up on the order of half of the impact. Land use is driven almost entirely by the materials phase. These results indicate that the materials and manufacturing stages are the most important to evaluate in the life cycle of paper towels because they are key drivers for all impact assessment methods.

The results of the contribution analysis indicate that the electricity and the natural gas used in the paper towel production are the primary contributors to the production GWP, making up approximately three-quarters of the impact, followed by pulp manufacturing. The exact breakdown, however, will depend on the pulp manufacturing process which, for the recycled-content towels, has larger uncertainty due to unit process inventory assumptions.

6.2 Sensitivity of results to scenarios and data quality

Numerous assumptions and inventory data decisions are made throughout the development of this study. The interpretation step of the study is used to explore the impact of those decisions on the outcomes.

The sensitivity analyses in Section 5.1 include tests of variations in thirteen assumptions on the outcomes of the study. Of these parameters, the electrical grid mix and the use intensity (time of use for hand dryers, number of pulls for cotton roll towels, and number of towels for paper towels) were shown to have the largest influence on GWP outcomes. The electrical grid mix assumption causes the most significant variation for the hand dryers because hand dryer GWPs are driven by the use phase, which relies on electricity. The GWPs of these systems can vary by an order of magnitude depending on the grid mix assumption. On the other hand, the paper towels and cotton roll towels are more affected by the use intensity assumption. Other parameters addressed in the sensitivity analyses were shown to have minimal effect (typically less than 10% deviation from the baseline) on drying system GWP.

The scenario uncertainty analysis tests numerous combinations of assumptions (i.e., scenarios) to determine the range of impacts that would result from these combinations. The analyses indicate that there is a wide range of possible GWP values for all of the scenarios: coefficients of variation (standard deviation divided by the mean) for the hand dryers were 50-60% and for the towels were 20-34%. The hand dryers have higher coefficients of variation because the electrical grid mix impacts them more than the towels. The scenario analysis results also show that variation in dryer system GWP is primarily driven by variation in use stage electric grid mix, whereas variation in towel system GWP is driven by changes in use intensity and manufacturing stage grid mix—consistent with results from the sensitivity analysis. The impact of the different levels of variation on comparative assertions is summarized in the following section.

The impact of data quality assumptions are tested using the uncertainty analyses, which rely on the pedigree matrix approach to quantify the uncertainty associated with data quality. The analyses indicate coefficients of variation of approximately 35% for the hand dryers and 12% for the towels using the baseline scenario.

6.3 Comparative assessment of product environmental impact

The results from this report may be used to make comparative assertions about hand-drying systems, so it is important to reiterate how the rank order of system impact is affected by impact assessment method and the statistical significance of the difference in the impact between the systems.

Table 9 compares rank order of drying systems for each impact assessment method. Systems are assigned the same rank if the difference between their impacts is within 10% of the lower of the two numbers. The results show that in general, the Dyson Airblade™ hand dryer systems have the lowest environmental impact and the paper towel and standard dryer systems have the highest impact, although the exact order ultimately depends on LCIA methodology.

A scenario uncertainty analysis and a bill of activities uncertainty analysis are used to evaluate the significance of the difference between drying system environmental impacts. Comparison indicator results from the scenario uncertainty analysis (Section 5.2.1) show that when drying-driven dry times are correlated across hand dryer systems, the XLERATOR® dryer's GWP is less than the Dyson Airblade™ hand dryer's GWP in fewer than 2% of the scenarios explored. This figure drops to well below 1% for each of the other systems examined. When drying times are modeled as time-driven, these figures grow to 7.3% for the XLERATOR®, 6.5% for the paper towels, and less than 1.3% for the other products. Removing dry time correlation between hand dryer systems increases the likelihood the impact of the XLERATOR® or standard dryers will be less than the impact of the aluminum Dyson Airblade™ hand dryer; the substitution of the printed wiring board unit process for the XLERATOR® and standard dryer control and optics assemblies has similar consequences (regardless of usage pattern). Thus, when dryers are used as recommended—that is, to dry hands completely as defined by the NSF Protocol P335—or even to just achieve a certain dryness—drying-driven usage—the aluminum Dyson Airblade™ hand dryer has a lower GWP than the XLERATOR® in 86% of the scenarios explored, and a lower GWP than the other drying systems in 98% or greater of the scenarios. When dryers are used interchangeably without regard to hand dryness (i.e. time-driven usage), it is less likely that the aluminum Dyson Airblade™ hand dryer will have the lower impact.

The second uncertainty analysis (Section 5.2.2) calculates a probability distribution of GWP using the baseline scenario and considering uncertainty and variation of unit process quantities in the bill of activities. The results of t-tests on these analyses (shown in Table 18) indicate that differences between the mean estimated impacts can be considered statistically significant for almost all drying system comparisons at an $\alpha = 0.01$ significance level. Exceptions include the comparisons between the standard dryer and paper towel distributions given both scenarios with reported dry times, and between the XLERATOR® dryer and the Dyson Airblade™ hand dryer distributions given reported dry times and use of the printed wiring board unit process for the XLERATOR®'s electronic components. Only the comparison between the standard dryer and paper towel distributions with the reported dry time baseline is statistically significant at a 5% significance level; the comparison between these two systems with the printed wiring board process for the standard dryer and between the XLERATOR® dryer and the Dyson Airblade™ hand dryer are not statistically significant at any level of significance.

It is important to include a comment from the ISO 14044 standard [11] about the care that should be used in employing comparative assertions:

> An LCIA shall not provide the sole basis of comparative assertion intended to be disclosed to the public of overall environmental superiority or equivalence, as additional information will be necessary to overcome some of the inherent limitations in the LCIA. Value-choices, exclusion of spatial and temporal, threshold and dose-response information, relative approach, and the variation in precision among impact categories are examples of such limitations. LCIA results do not predict impacts on category endpoints, exceeding thresholds, safety margins or risks.

Thus, although this study may be used as a foundation for comparative assertions about environmental performance, the assertions should also include other information about the relative performance of the products to strengthen the claims.

6.4 Recommendations for reducing drying system environmental impact

Another goal of the study is to identify ways to reduce the environmental impact of the products, thereby informing design decisions. Based on the key drivers of environmental impact identified in this study, opportunities exist for reducing product impact. The opportunities for hand dryers include:

- Reducing product electricity consumption during operation.
- Shortening dry times (if possible).
- Replacing virgin aluminum with less impact-intensive materials (including recycled aluminum).
- Using control and optics assemblies with a lower environmental footprint.
- Decreasing electricity burden associated with product assembly.

The opportunities for cotton roll towels include:

- Limiting use to one pull per dry.
- Using materials that have lower water and land occupation burdens.
- Reducing burden of spinning and weaving processes.
- Decreasing natural gas consumption during washing processes (e.g., colder temperature washing).

The opportunities for paper towels include:

- Limiting use to one paper towel per dry.
- Reducing natural gas and electricity consumption during the material production phase.
- Collecting material at end-of-life to prevent it from degrading in landfills.

6.5 Study limitations

There are several limitations of this study that need to be considered when interpreting the results.

- Data from other studies were applied without having direct access to the practitioners and commissioners of those studies. Sensitivity analyses were used in instances where assumptions or data in other studies were unclear.
- Inventory data for production of deinked pulp from 100% recycled content was not available; thus, simplifying assumptions were made for the deinked pulp manufacturing process. It is difficult to assess exactly how this assumption impacts the results because the Kimberly-Clark study calculates at 30% *increase* in GWP impact for recycled paper towels over virgin paper towels [13], whereas the Paper Task Force [58] noted in a 1995 report on printing paper that deinked pulp production consumes less energy and more bleaching chemicals than bleached kraft pulp production. Improved inventory data on recycled paper towels would help to clarify these discrepancies.
- European data (ecoinvent) and methods (IMPACT 2002+) were applied to a US context. This is necessary because of limited data availability for the US context.
- Data on observed hand drying times, which is a key driver of environmental impact, were not available for all hand dryers. However, the scenario analyses explored the impact of variation in hand drying times.
- No uncertainty analysis was conducted using the LCIA methodologies because the methodologies do not provide information on the degree of variation for the characterization factors. Thus, such an analysis is not possible at the moment.

- The pedigree matrix approach to estimating uncertainty in an inventory uses subjective data quality assessments and uncertainty values to quantify uncertainty. However, the data source quality assessments were applied consistently across all products, so the uncertainty assessments for all products can be used to make meaningful relative comparisons.

In spite of these limitations, the scenario analyses and the uncertainty analyses have shown that the results of the study are robust for a wide range of scenarios and data assumptions. Thus, the limitations do not fundamentally diminish the outcomes of the study.

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8 Critical review

A critical review of this report has been conducted by a peer review committee of LCA experts. The committee consisted of H. Scott Matthews (Avenue C Advisors, LLC) who served as the chair of the panel and Jeff Morris (Sound Resource Management Group) and Cynthia Manson (Industrial Economics, Inc.). The committee found the report to be in compliance with the ISO 14040/14044 standards. Furthermore, the committee had numerous suggestions on how to improve the content and quality of the report. Most of these suggestions have been implemented in this report. A full list of the committee's comments on the report is included in a separate document.

A Appendices

A.1 Hand-drying system bills of activities

Bill of activities data for each of the hand-drying systems is detailed in Tables 19 and 20 in this appendix. The data represent the materials and processes required to dry a single pair of hands—that is, one functional unit. It should also be noted that within each life cycle stage, the data is consolidated by material or process rather than by part.

Table 19 Bill of activities data representing one functional unit of hand dryer systems.

Life cycle stage	Unit process	Unit	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer
Materials						
	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant (RER)	mg	0.302	0.302	1.62	0.405
	Adhesive for metals, at plant (DE)	mg	0.086	0.086	—	—
	Aluminium, primary, at plant (RER)	mg	25.7	—	—	2.797
	Aluminium, secondary, from old scrap, at plant (RER)	mg	—	—	—	2.797
	Ceramic tiles, at regional storage (CH)	mg	—	—	—	0.302
	Chromium, at regional storage (RER)	mg	—	—	0.016	—
	Copper, primary, at refinery (RER)	mg	0.029	0.029	0.966	0.767
	Electronic component, active,nspecified, at plant (GLO)	mg	—	—	0.669	0.669
	Epoxy resin, liquid, at plant (RER)	mg	—	—	0.025	—
	Galvanized steel	mg	—	—	—	6.24
	Glass fiber reinforced polypropylene	mg	2.81	2.807	—	—
	Glass fibre reinforced plastic, polyamide, injection molding, at plant (RER)	mg	—	—	4.01	—
	Glass fibre, at plant (RER)	mg	0.494	0.494	—	—
	Melamine, at plant (RER)	mg	1.70	1.703	—	—
	Nickel, 99.5%, at plant (GLO)	mg	—	—	0.0056	—
	Nylon 6, at plant (RER)	mg	—	—	—	0.342
	Paper, newsprint, at regional storage (RER)	mg	0.483	0.483	—	—
	Plastic mixture with extrusion	mg	—	—	1.25	—
	Polycarbonate, at plant (RER)	mg	0.464	9.401	—	—
	Polyethylene terephthalate, granulate, amorphous, at plant (RER)	mg	—	—	—	0.179
	Polyethylene, LDPE, granulate, at plant (RER)	mg	0.459	0.459	—	—
	Polypropylene, granulate, at plant (RER)	mg	3.24	3.239	—	—
	Polystyrene, general purpose, GPPS, at plant (RER)	mg	1.89	1.89	—	—
	Polyurethane, rigid foam, at plant (RER)	mg	0.063	0.063	—	—
	Polyvinylchloride, at regional storage (RER)	mg	0.493	0.493	—	—
	Stainless steel sheet	mg	6.14	11.03	—	—
	Steel, converter, chromium steel 18/8, at plant (RER)	mg	1.31	1.309	9.67	3.80
	Synthetic rubber, at plant (RER)	mg	2.05	2.050	—	—

Life cycle stage	Unit process	Unit	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer
Materials (cont'd)						
	Zinc, primary, at regional storage (RER)	mg	—	—	7.02	1.61
	Printed wiring board, through-hole, lead-free surface, at plant (GLO)	mm^2	0.051	0.051	—	—
	Sawn timber, softwood, planed, kiln dried, at plant (RER)	cm^3	—	—	—	0.001
	Unspecified mass	mg	—	—	4.82	0.483
Packaging	Corrugated board, fresh fibre, single wall, at plant (RER)	mg	—	—	0.376	1.47
Packaging	Corrugated board, recycling fibre, single wall, at plant (RER)	mg	—	8.297	0.376	—
Packaging	Packaging film, LDPE, at plant (RER)	mg	—	—	0.150	—
Manufacturing						
	Electricity, medium voltage, at grid (CN)	kJ	0.420	0.423	0.445	0.445
	Natural gas, burned in industrial furnace low-NOx >100kW (RER)	kJ	—	—	0.474	0.474
	Water, unspecified natural origin	cm^3	0.013	0.0183	—	—
	Treatment, sewage, to wastewater treatment, class 3 (CH)	cm^3	0.013	0.0181	—	—
Use						
	Electricity, low voltage, at grid (US)	kJ	17.2	17.2	31.6	92.2
End-of-life						
	Recycling cardboard	mg	6.36	6.36	0.576	1.13
	Disposal, municipal solid waste, to landfill, methane energy recovery	mg	40.8	31.1	24.6	17.2
	Disposal, municipal solid waste, to incineration, energy recovery	mg	9.56	7.30	5.77	4.03
Transportation						
To plant	Transport, lorry >16t, fleet average (RER)	kgkm	0.0142	0.0112	0.0077	0.0056
To US port	Transport, transoceanic freight ship (OCE)	kgkm	0.533	0.386	0.290	0.205
To warehouse	Transport, freight, rail, diesel (US)	kgkm	0.132	0.0957	0.0719	0.0509
To warehouse	Transport, lorry >32t, EURO3 (RER)	kgkm	0.0012	0.00088	0.00066	0.00047
To washroom	Transport, lorry 16-32t, EURO3 (RER)	kgkm	0.0894	0.0648	0.0487	0.0344
To waste facility	Transport, lorry 7.5-16t, EURO3 (RER)	kgkm	0.0051	0.0037	0.0028	0.0020
References			[27]	[27]	[14, 27]	[14, 27]
Reference flow			1/350,000 of dryer and packaging Electricity to dry one pair of hands			

Table 20 Bill of activities data representing one functional unit of towel systems.

Life cycle stage	Unit process	Unit	Cotton roll towels	Paper towels	Dispenser	Waste bin and liners
Materials						
	Copper, primary, at refinery (RER)	mg	—	—	0.483	—
	Cotton fibres, ginned, at farm (CN)	mg	178	—	—	—
	Polyethylene, LDPE, granulate, at plant (RER)	mg	—	—	—	126
	Polypropylene, granulate, at plant (RER)	mg	—	—	9.13	—
	Steel, converter, chromium steel 18/8, at plant (RER)	mg	—	—	0.483	20.4
	Sulphate pulp, ECF bleached, at plant (RER)	mg	—	4,112	—	—
	Pulp from waste paper	mg	—	(4,112)[a]	—	—
Packaging	Corrugated board, fresh fibre, single wall, at plant (RER)	mg	—	414	0.648	10.1
Packaging	Packaging film, LDPE, at plant (RER)	mg	90.2	—	—	—
Manufacturing						
	Electricity, medium voltage, at grid (CN)	kJ	—	—	0.445	—
	Electricity, low voltage, at grid (US)	kJ	—	29.4	—	—
	Natural gas, burned in industrial furnace low-NOx >100kW (RER)	kJ	—	48.7	0.474	—
	Water,nspecified natural origin	L	—	0.212	—	—
	Treatment, sewage, to wastewater treatment, class 3 (CH)	L	—	0.212	—	—
	Extrusion, plastic film (RER)	mg	—	—	—	126
	Extrusion, plastic pipes (RER)	mg	—	—	7.98	—
	Spinning cotton fiber	mg	160	—	—	—
	Sizing	mg	160	—	—	—
	Weaving	mg	157	—	—	—
	De-sizing / scouring / bleaching	mg	157	—	—	—
Use						
	Laundering	g	16.2	—	—	—
End-of-life						
	Recycling cardboard	mg	—	317	0.496	7.75
	Disposal, municipal solid waste, to landfill, methane energy recovery	mg	218	3,410	8.30	120
	Disposal, municipal solid waste, to incineration, energy recovery	mg	51.0	800	1.95	28.2

Life cycle stage	Unit process	Unit	Cotton roll towels	Paper towels	Dispenser	Waste bin and liners
Transportation						
To plant	Transport, lorry >16t, fleet average (RER)	kgkm	0.0671	1.13	0.0027	0.039
To US port	Transport, transoceanic freight ship (OCE)	kgkm	1.65	—	0.098	1.57
To warehouse	Transport, freight, rail, diesel (US)	kgkm	0.409	—	0.0243	0.388
To warehouse	Transport, lorry >32t, EURO3 (RER)	kgkm	0.0038	—	0.00022	0.0036
To washroom	Transport, lorry 16-32t, EURO3 (RER)	kgkm	0.277	7.60	0.0164	0.262
To laundry	Transport, lorry 3.5-7.5t, EURO3 (RER)	kgkm	1.62	—	—	—
To waste facility	Transport, lorry 7.5-16t, EURO3 (RER)	kgkm	0.024	0.432	0.00093	0.015
References			[12]	[12-14]	[14]	[6, 14]
Reference flow			1/103 of one towel pull and packaging, plus laundry	2 paper towels	1/350,000 of dispenser and packaging	1/350,000 of waste bin & pkging, plus 1/270 of bin liner & pkging

(a) Parentheses indicate masses associated with paper towels manufactured from 100% recycled content (assuming cut-off allocation of that content).

A.1.1 Energy consumption calculations for dryer use stage

As noted in Section 3.1.2, hand dryers consume energy not only when actively drying hands, but also when spinning down and when in standby mode (due to their use of optical switches to sense when to turn on and off). Spin-down energy consumption is estimated by assuming a 1.5-second spin-down time at half power. Standby energy consumption is calculated based on the dryer's standby power rating and the total time in the 5-year dryer life span, less the time the dryer is in-use or spinning down. Total energy consumption can therefore be written as:

$$E = P_{in-use} t_{in-use} + P_{spin-down} t_{spin-down} + P_{standby} t_{standby}$$

where P_x and t_x represent the in-use, spin-down, and standby power ratings and times, respectively. t_{in-use} is given by the measured (or reported) times in Table 4; additional power ratings and times can be found in Table 5. $t_{standby}$ is calculated from t_{in-use} and $t_{spin-down}$ following:

$$t_{standby} = \frac{t_{life\_span} - lifetime\_usage \cdot \left(t_{in-use} + t_{spin-down}\right)}{lifetime\_usage}$$

t_{life_span} represents a dryer's 5-year life span and *lifetime_usage* the pairs of dry hands dried over the 5-year time frame (equal to 350,000 pairs in this study). Total energy consumption is thus

$$\begin{aligned} E &= P_{in-use}t_{in-use} + P_{spin-down}t_{spin-down} + P_{standby}t_{standby} \\ &= P_{in-use}t_{in-use} + \frac{1}{2}P_{in-use} \cdot (1.5\,\text{sec}) + P_{standby} \cdot \frac{158\times10^{6}\,\text{sec} - 350{,}000 \cdot \left(t_{in-use} + 1.5\,\text{sec}\right) \cdot}{350{,}000} \end{aligned}$$

A.2 Modified unit process data

Tables 22 – 36 present unit processes needed for this study, but not available in the ecoinvent database. These processes were either adapted or created using ecoinvent data or adopted from external sources. The modified processes include:

- Galvanized steel (Table 22) – The quantity of the "zinc coating" required was estimated by calculating the area of a 0.7-mm thick square of steel weighing one kilogram. Given that the zinc remaining on the steel is approximately 45 mm [32], it adds less than 12 g to overall mass and is therefore not counted in the process.

- Stainless steel sheet (Table 23) – This process assumes stainless steel is rolled into sheets and that there are no losses from rolling.

- Plastic mixture with extrusion (Table 24) – Because of lack of specific data in the Excel study [14], this process was created to provide a generic plastic process for the XLERATOR and standard dryers. It also assumes there are no losses from processing.

- Glass fiber reinforced polypropylene (Table 25) – This process was created specifically for the Dyson Airblade™ hand dryers; it assumes the same amount of electricity consumption as the PC/ABS process (Table 26).

- Polycarbonate / Acrylonitrile-butadiene-styrene (Table 26) – Process data were obtained from Dyson [27] and assume a 3% material loss.

- Cotton towel production and laundering (Tables 27 – 31) – Process data were obtained from the ETSA study [12].

- Pulp from waste paper (Table 32) – This process makes the assumption that the input and output flows from manufacturing pulp from waste paper are equal to those of manufacturing ECF-bleached sulfate pulp from virgin wood. The only exception is that instead of wood, waste paper is used. Only a partial inventory is shown because the unit process is adopted from the ecoinvent unit process for ECF-bleached sulfate pulp.

- Cardboard recycling (Table 33) – The avoided production of cardboard is calculated assuming each kilogram of recycled paper still requires 0.22 kg of virgin fibers [12].

- Incineration with energy recovery (Table 34) – The ecoinvent process for municipal solid waste incineration (Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH U) is modified to include the avoided production of 0.65 kWh of electricity per kilogram of waste incinerated [38]. This electricity is assumed to replace electricity production on the US average grid mix, thus leading to the avoided emissions of 0.632 g CO_2 eq per kilogram of waste incinerated. These emissions from the avoided production of electricity are credited to the drying systems. Table 34 only includes a subset of process inputs and emissions; flows not included are the same as those in the unmodified ecoinvent process.

- Landfill with methane capture (Table 35) – The ecoinvent process for municipal solid waste landfill (Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U) is modified to account for methane capture of landfill emissions and the subsequent combustion of such emissions with energy recovery to produce electricity. Seventy-five percent of methane emissions—from both biogenic and fossil sources—are captured [46] for a total of 16.2 g of methane per kilogram of waste. These captured emissions are burned and completely converted to carbon dioxide, which is released into the atmosphere (4.43 g CO_2 per kilogram of waste). Heat from the combustion reaction is recovered (the lower heating value of methane, 802 kJ / kg CH_4, is assumed) and used to produce electricity. Given an efficiency of 11,600 MJ per kWh [46], 251 J (6.97×10^{-5} kWh) of electricity is generated and assumed to replace production on the US average grid. All emissions from the avoided production of electricity are credited to the drying systems. Table 35 only includes a subset of process inputs and emissions; flows not included are the same as those in the unmodified ecoinvent process.

- Composting (Table 36) – Composting towels in place of sending them to a landfill or incinerator is analyzed in the sensitivity analysis (Section 5.1.5). This process assumes that the compost generated allows the avoided production of fertilizer, the mass of which is calculated based on data from ecoinvent and a European Commission study on biodegradable municipal waste [32, 47]. Calculation results are shown in Table 21. These results assume that 1 kg dry matter displaces 18.9 g N, 4.86 g P_2O_5, and 11.7 g K_2O over 10 years, and that 1 kg of biodegradable waste yields 350 g compost, which contains 60% dry matter. Nutrient displacement values represent data for an average compost, which includes some fraction of kitchen scraps and yard waste, because no data is available for paper- or cotton-only compost. Fertilizer types are selected based on usage data from the USDA Economic Research Service [59] and weight fractions of nutrients in each fertilizer are taken from ecoinvent documentation [32]. The calculated mass of displaced urea-ammonium nitrate accounts for the presence of nitrogen in monoammonium phosphate, the phosphorus fertilizer.

Table 21 Avoided fertilizer production assumptions for compost end-of-life scenario.

Nutrient	Mass displaced per kg dry matter	Mass displaced per kg compost	Mass displaced per kg waste	Fertilizer	Nutrient weight %	Fertilizer displaced per kg waste
Nitrogen	18.9 g	11.3 g	3.95 g	Urea-ammonium nitrate	32%	11.7 g
				Monoammonium phosphate	11%	—
Phosphorus	4.9 g	2.9 g	1.02 g	Monoammonium phosphate	52%	2.0 g
Potassium	11.7 g	7.0 g	2.45 g	Potassium chloride	60%	4.1 g

Table 22 Unit process for galvanized steel.

Unit Process: Galvanized steel

Inputs			Outputs		
Name	Amount	Unit	Name	Amount	Unit
Chromium steel (RER)	1	kg	Galvanized steel	1	kg
Zinc coating (RER)	0.1815	m^2			

Table 23 Unit process for stainless steel sheet.

Unit Process: Stainless steel sheet

Inputs			Outputs		
Name	Amount	Unit	Name	Amount	Unit
Chromium steel (RER)	1	kg	Sheet steel	1	kg
Sheet rolling (RER)	1	kg			

Table 24 Unit process for plastic mixture with extrusion.

Unit Process: Plastic mixture with extrusion

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Polypropylene (RER)	1	kg	Plastic mixture with extrusion	1	kg
Extrusion (RER)	1	kg			

Table 25 Unit process for glass fiber reinforced polypropylene.

Unit Process: Glass fiber reinforced polypropylene

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Glass fiber (RER)	0.3	kg	Glass fiber reinforced PP	1	kg
Polypropylene (RER)	0.7	kg			
Electricity (CN)	0.3	kWh			

Table 26 Unit process for polycarbonate / acrylonitrile-butadiene-styrene.

Unit Process: Polycarbonate / Acrylonitrile-butadiene-styrene [27]

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Polycarbonate (RER)	0.721	kg	PC/ABS	1	kg
ABS copolymer (RER)	0.309	kg			
Electricity (CN)	0.3	kWh			

Table 27 Unit process for spinning (cotton towels).

Unit Process: Spinning cotton fiber [12]

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Electricity (CN)	7.67	MJ	Spun cotton fiber	1	kg
Natural gas (RER)	2.5	MJ			

Table 28 Unit process for sizing (cotton towels).

Unit Process: Sizing [12]

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Starch (DE)	0.1	kg	Sized fiber	1	kg

Table 29 Unit process for weaving (cotton towels).

Unit Process: Weaving [12]

Inputs			**Outputs**		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Electricity (CN)	15.2	MJ	Woven cotton towel	1	kg
Natural gas (RER)	13.9	MJ			

Table 30 Unit process for de-sizing, scouring, and bleaching (cotton towels).

Unit Process: De-sizing / scouring / bleaching [12]

Inputs			**Outputs**		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Water	0.162	m^3	Bleached cotton towel	1	kg
Hydrogen peroxide (RER)	0.45	kg			
Sodium hydroxide (RER)	0.055	kg	*To water*		
Electricity (CN)	3.6	MJ	Ammonium	1.6	g
Natural gas (RER)	14.9	MJ	Nitrogen	2.9	g
			Phosphorus	0.24	g
			Sewage (CH)	0.162	m^3

Table 31 Unit process for laundering (cotton towels).

Unit Process: Laundering

Inputs			**Outputs**		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Water	9.4	L	Washed cotton towel	1	kg
Soap (RER)	26.1	g			
Electricity (US)	0.1	kWh	Sewage (CH)	9.4	L
Natural gas (RER)	4.1	MJ			

Table 32 Partial unit process inventory for producing pulp from waste paper.

Unit Process: Pulp from waste paper

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Water	0.074	m^3	Bleached sulfate pulp	1	kg
Waste paper (RER)	1.5	kg			
Quicklime (CH)	0.0084	kg	*To air*		
Carbon dioxide liquid (RER)	0.001	kg	Heat, waste	5.26	MJ
Hydrogen peroxide (RER)	0.0054	kg	Carbon dioxide, biogenic	2.21	kg
Sulfuric acid (RER)	0.0301	kg	«Same as ecoinvent process»		
…					
			To water		
			«Same as ecoinvent process»		
			Disposal, hazardous waste (DE)	0.00026	kg
			«Same as ecoinvent process»		

Table 33 Unit process for cardboard recycling.

Unit Process: Cardboard recycling

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Corrugated board (RER)	1	kg	Corrugated board	1	kg
Avoided production					
Corrugated board (RER)	0.78	kg			

Table 34 Unit process for incineration with energy recovery.

Unit Process: Incineration with energy recovery

Inputs			Outputs		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Municipal solid waste	1	kg	*Emissions*		
			«Same as ecoinvent process»		
Additional inputs					
«Same as ecoinvent process»					
Avoided production					
Electricity (US)	0.65	kWh			

Table 35 Unit process for landfill with methane capture and energy recovery.

Unit Process: Landfill with methane capture and energy recovery

Inputs			**Outputs**		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Municipal solid waste	1	kg	*To air*		
			Carbon dioxide, biogenic	182	g
Avoided production			Carbon dioxide, fossil	8.30	g
Electricity (US)	251	J	Methane, biogenic	5.15	g
			Methane, fossil	0.236	g
Additional inputs					
«Same as ecoinvent process»			*Additional emissions*		
			«Same as ecoinvent process»		

Table 36 Unit process for composting as a waste treatment option.

Unit Process: Compost (waste treatment) [32, 47]

Inputs			**Outputs**		
Name	**Amount**	**Unit**	**Name**	**Amount**	**Unit**
Biodegradable waste	1	kg	Compost	0.35	kg
Diesel (RER)	0.291	g			
Electricity (US)	0.0175	kWh	*To air*		
			Ammonia	130	mg
Avoided product			Carbon dioxide	124	G
Urea ammonium nitrate	11.7	g	Carbon monoxide	9.29	mg
Monoammonium phosphate	2.0	g	Hydrocarbons, unspecified	3.81	mg
Potassium chloride	4.1	g	Hydrogen chloride	0.013	mg
			Hydrogen fluoride	0.013	mg
			Methane	344	mg
			Nitrogen oxides	15.73	mg
			Particulates	0.897	mg
			Sulfur oxides	3.54	mg
			VOC	8.4	mg
			To water		
			BOD	0.013	mg
			COD	0.013	mg
			TOC	0.145	mg
			Chlorine	0.013	mg
			Fluorine	0.013	mg
			Metallic ions	0.013	mg
			Phenol	0.013	mg
			Suspended solids	0.013	mg

A.3 Unit process impact and quality

Environmental impacts of the unit processes used in the bill of activities (Tables 19 and 20) are listed in Table 38. Quality levels and the basic uncertainty factor required in the pedigree matrix analysis are also detailed for each process in Table 39.

A.3.1 Statistical tests

Two statistical tests are used to evaluate the results of the data quality analysis (Section 5.2.2): the t-test and the chi-square goodness of fit test. T-test is used to compare GWP distribution means and determine whether their differences are statistically significant. For this particular analysis, the following equation is used to test whether the impact of drying system A is lower than that of drying system B:

$$t_o = \frac{\bar{y}_A - \bar{y}_B}{\sqrt{\frac{S_A^2}{n_A} + \frac{S_B^2}{n_B}}}$$

$\bar{y}$ represents the sample mean, S^2 the sample variance, and n the sample size of each system. The test is considered to be statistically significant—i.e. the impact of system A is likely lower than the impact of system B—if $t_o < -t_{\alpha,v}$ where α is the significance level of the test and v the degrees of freedom. In this case, the significance level represents the probability of stating that the impact of drying system A is lower than that of drying system B when, in fact, their distributions and means are statistically indistinguishable (i.e. the samples were drawn from the same population). Typically α is chosen to be equal to or less than 0.05—thus, a 5% chance that the statement that drying system A has the lower impact is incorrect—for statistical significance. The degrees of freedom, v, is calculated from the sample variances and sample sizes:

$$v = \frac{\left(\frac{S_A^2}{n_A} + \frac{S_B^2}{n_B}\right)^2}{\frac{\left(S_A^2/n_A\right)^2}{n_A - 1} + \frac{\left(S_B^2/n_B\right)^2}{n_B - 1}}$$

v and t_o are calculated for each drying system comparison; $t_{\alpha,v}$ is obtained from a look-up table and depends on choice of α (as well as value of v). Table 37 summarizes the resulting t_o values from each comparison of the drying system GWP distributions in Section 5.2.2. $-t_{\alpha,v}$ for all t-tests varied from −2.358 to −2.345 for $\alpha = 0.01$ and from −1.658 to −1.653 for $\alpha = 0.05$. Only in three instances is t_o greater than $-t_{\alpha,v}$: the comparison between the standard dryer and paper towels systems given both scenarios with reported dry times, and the comparison between the Dyson Airblade™ hand dryer and the XLERATOR® dryer systems given manufacturer-reported dry times and the use of the printed wiring board unit process for the XLERATOR®'s optics and control assemblies

Since the t-test requires that each sample be normally distributed, the chi-square goodness of fit test is applied to assess the appropriateness of modeling GWP distributions as either normal or lognormal.

This test compares a GWP distribution to a normal or lognormal distribution with a mean and standard deviation estimated from the GWP sample. Goodness of fit is then measured by summing the squares of differences between observed (O) and expected (E) outcomes, divided by the expected outcome:

$$Q = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

The null hypothesis—that is, the GWP distribution and the predicted normal or lognormal model are drawn from the same population and thus represent the same distribution—is true if

$$Q < \chi_{\alpha}^{2}(r)$$

where α is the significance level and r the degrees of freedom. For this test, r equals $k - 3$ (degrees of freedom are lost because the mean and standard deviation are estimated from the sample). The chi-square test is chosen from among other goodness of fit tests because it is applicable to the binned GWP data obtained from SimaPro.

Table 37 Results for t-test statistics for drying system GWP distributions in Section 5.2.2.

		Baseline, measured	Baseline, reported	PWB, use intensity, measured
Drying system A	**Drying system B**	t_o	t_o	t_o
Airblade™, aluminum	XLERATOR®	-12	-3.2	0.3
Airblade™, aluminum	Standard dryer	-28	-28	-27
Airblade™, aluminum	Cotton roll towels	-26	-26	-26
Airblade™, aluminum	Paper towels, virgin	-35	-35	-35
XLERATOR®	Standard dryer	-17	-25	-25
XLERATOR®	Cotton roll towels	-11	-22	-23
XLERATOR®	Paper towels, virgin	-20	-31	-31
Cotton roll towels	Standard dryer	-12	-711	-11
Cotton roll towels	Paper towels, virgin	-19	-19	-19
Standard dryer	Paper towels, virgin	-2.8	-2.2	-1.4

Table 38 Environmental impact of unit processes.

Unit process	Units	Source	GWP v1.02 (IPCC 2007 100a) [kg CO_2 eq]	IMPACT 2002+ Human health [10^{-6} DALY]	IMPACT 2002+ Ecosys. quality [PDF.m^2.yr]	IMPACT 2002+ Climate change [kg CO_2 eq]	IMPACT 2002+ Resources [MJ primary]	CED v1.07 [MJ]	Water consumption [m^3]	Land occupation [m^2.org.arable]
Materials										
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant	kg	ecoinvent 2.1	4.39	5.60	0.100	3.86	101	99.3	0.694	9.32E-4
Adhesive for metals, at plant	kg	ecoinvent 2.1	4.51	4.59	0.218	4.15	90.2	88.7	1.70	0.00502
Aluminium, primary, at plant	kg	ecoinvent 2.1	12.2	10.2	2.44	12.6	163	194	323	0.0374
Aluminium, secondary, from old scrap, at plant	kg	ecoinvent 2.1	1.38	0.886	1.58	1.32	22.7	23.8	6.91	0.0156
Ceramic tiles, at regional storage	kg	ecoinvent 2.1	0.780	6.48	0.184	0.750	14.4	14.7	3.30	0.0181
Chromium, at regional storage	kg	ecoinvent 2.1	26.7	18.5	6.16	26.1	467	577	1,291	0.0640
Copper, primary, at refinery	kg	ecoinvent 2.1	1.85	14.7	12.5	1.77	29.5	34.5	60.4	0.0298
Corrugated board, fresh fibre, single wall, at plant	kg	ecoinvent 2.1	0.981	0.899	1.10	0.942	15.1	45.2	4.48	0.744
Corrugated board, recycling fibre, single wall, at plant	kg	ecoinvent 2.1	0.982	0.414	0.432	0.939	15.0	15.8	1.01	0.0900
Cotton fibres, ginned, at farm (China)	kg	ecoinvent 2.1	3.50	3.78	12.2	2.58	32.0	51.1	12.3	8.17
Electronic component, active, unspecified, at plant	kg	ecoinvent 2.1	735	598	348	715	11,800	12,352	3,766	4.02
Epoxy resin, liquid, at plant	kg	ecoinvent 2.1	6.72	7.19	0.258	6.15	138	135	0.452	6.30E-4
Galvanized steel	kg	Modified	5.56	11.6	9.52	5.36	89.9	92.2	127	0.0448
Glass fiber reinforced polypropylene	kg	Modified	2.52	2.32	0.163	2.30	69.9	69.8	2.81	0.00361
Glass fibre reinforced plastic, polyamide, injection moulding, at plant	kg	ecoinvent 2.1	8.80	3.59	0.260	8.07	148	148	6.91	0.0175
Glass fibre, at plant	kg	ecoinvent 2.1	2.63	2.64	0.414	2.49	45.7	45.9	7.81	0.00689
Melamine, at plant	kg	ecoinvent 2.1	5.07	3.24	0.637	4.86	103	101	8.04	0.0199
Nickel, 99.5%, at plant	kg	ecoinvent 2.1	10.8	96.3	30.8	10.6	148	187	429	0.135
Nylon 6, at plant	kg	ecoinvent 2.1	9.27	3.91	0.159	7.22	125	122	0.263	2.58E-4
Packaging film, LDPE, at plant	kg	ecoinvent 2.1	2.70	1.44	0.112	2.38	91.3	92.7	3.02	0.0209

Unit process	Units	Source	GWP v1.02 (IPCC 2007 100a) [kg CO_2 eq]	IMPACT 2002+ Human health [10^{-6} DALY]	IMPACT 2002+ Ecosys. quality [PDF.m^2.yr]	IMPACT 2002+ Climate change [kg CO_2 eq]	IMPACT 2002+ Resources [MJ primary]	CED v1.07 [MJ]	Water consumption [m^3]	Land occupation [m^2.org.arable]
Materials (cont'd)										
Paper, newsprint, at regional storage	kg	ecoinvent 2.1	1.28	1.02	0.495	1.23	24.8	42.0	10.8	0.251
Plastic mixture with extrusion	kg	Modified	2.35	1.83	0.080	2.14	83.0	83.2	2.22	0.0117
Polycarbonate / Acrylonitrile-butadiene-styrene	kg	[27]	7.32	5.30	0.144	6.24	114	112	0.782	0.00196
Polyethylene, LDPE, granulate, at plant	kg	ecoinvent 2.1	2.10	1.13	0.0296	1.81	79.8	79.5	0.0654	8.53e-5
Polyethylene terephthalate, granulate, amorphous, at plant	kg	ecoinvent 2.1	2.70	4.67	0.268	2.48	78.7	78.4	5.77	0.00903
Polypropylene, granulate, at plant	kg	ecoinvent 2.1	1.97	1.61	0.0241	1.77	75.8	75.1	0.0560	5.46e-5
Polystyrene, general purpose, GPPS, at plant	kg	ecoinvent 2.1	3.50	1.38	0.0616	2.97	89.4	87.9	0.166	9.58e-5
Polyurethane, rigid foam, at plant	kg	ecoinvent 2.1	4.31	2.75	0.145	3.73	102	103	2.59	0.00325
Polyvinylchloride, at regional storage	kg	ecoinvent 2.1	2.00	0.642	0.0536	1.92	60.5	60.3	0.558	3.72e-4
Printed wiring board, through-hole, lead-free surface, at plant	m^2	ecoinvent 2.1	105	75.6	75.8	99.4	1,901	1,975	573	0.614
Sawn timber, softwood, planed, kiln dried, at plant	m^3	ecoinvent 2.1	122	172	373	119	2,224	12,709	526	291
Stainless steel sheet	kg	Modified	4.99	10.2	4.81	4.80	82.8	84.1	121	0.0441
Steel, converter, chromium steel 18/8, at plant	kg	ecoinvent 2.1	4.44	9.50	4.53	4.28	72.4	73.4	113	0.0405
Sulphate pulp, ECF bleached, at plant	kg	ecoinvent 2.1	0.670	0.933	1.23	0.501	8.56	55.3	2.31	1.05
Pulp from waste paper	kg	Modified	0.491	0.967	0.11	0.553	9.26	9.57	1.98	0.00329
Synthetic rubber, at plant	kg	ecoinvent 2.1	2.64	1.77	0.326	2.50	89.9	91.3	6.65	0.0191
Unspecified mass	kg	Modified	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zinc, primary, at regional storage	kg	ecoinvent 2.1	3.37	7.22	22.3	3.22	48.8	56.0	70.6	0.0176
Water, unspecified natural origin	m^3	raw	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0

Unit process	Units	Source	GWP v1.02 (IPCC 2007 100a) [kg CO_2 eq]	IMPACT 2002+ Human health [10^{-6} DALY]	IMPACT 2002+ Ecosys. quality [PDF.m^2.yr]	IMPACT 2002+ Climate change [kg CO_2 eq]	IMPACT 2002+ Resources [MJ primary]	CED v1.07 [MJ]	Water consumption [m^3]	Land occupation [m^2.org.arable]
Processing										
Extrusion, plastic film	kg	ecoinvent 2.1	0.526	0.261	0.0750	0.509	9.34	10.9	2.83	0.0201
Extrusion, plastic pipes	kg	ecoinvent 2.1	0.378	0.228	0.0557	0.367	7.17	8.06	2.17	0.0117
Spinning cotton fiber	kg	[12]	2.68	2.88	0.163	2.41	25.4	27.2	3.08	0.0107
Sizing	kg	[12]	0.121	0.0867	0.370	0.0991	1.40	3.42	0.181	0.178
Weaving	kg	[12]	5.95	5.79	0.341	5.38	61.8	65.0	6.30	0.0214
De-sizing / scouring / bleaching	kg	[12]	2.85	2.45	1.28	2.65	41.9	42.2	4.37	0.00793
Laundering	kg	[12]	0.418	0.176	0.128	0.400	7.11	8.18	0.565	0.0435
Treatment, sewage, to wastewater treatment, class 3	m^3	ecoinvent 2.1	0.382	0.933	6.89	0.349	5.25	5.67	3.17	0.00494
Energy										
Electricity, medium voltage, at grid (China)	MJ	ecoinvent 2.1	0.327	0.372	0.0207	0.293	2.89	3.14	0.395	0.00139
Natural gas, burned in industrial furnace low-NOx >100kW	MJ	ecoinvent 2.1	0.070	0.0092	0.0020	0.0671	1.29	1.24	0.0213	1.67e-5
Electricity, medium voltage, at grid (US)	MJ	ecoinvent 2.1	0.214	0.161	0.0306	0.207	3.44	3.56	0.8287	5.09e-4
Electricity, low voltage, at grid (US)	MJ	ecoinvent 2.1	0.232	0.178	0.053	0.225	3.73	3.86	0.904	5.86e-4
End-of-life										
Recycling cardboard	kg	ecoinvent 2.1	0.217	-0.287	-0.425	0.204	3.23	-19.4	-2.48	-0.490
Disposal, municipal solid waste, to landfill, methane energy recovery	kg	ecoinvent 2.1	0.142	0.0236	0.0068	0.0454	0.40	0.418	0.109	0.00151
Disposal, municipal solid waste, to incineration, energy recovery	kg	ecoinvent 2.1	0.325	-0.021	-0.10	0.341	-8.31	-8.60	-2.03	-1.1e-3
Compost	kg	[32, 47]	0.381	-0.019	-0.002	0.0787	-0.673	-0.652	-0.022	-2.7e-4

Unit process	Units	Source	GWP v1.02 (IPCC 2007 100a) [kg CO_2 eq]	IMPACT 2002+ Human health [10^{-6} DALY]	IMPACT 2002+ Ecosys. quality [PDF.m^2.yr]	IMPACT 2002+ Climate change [kg CO_2 eq]	IMPACT 2002+ Resources [MJ primary]	CED v1.07 [MJ]	Water consumption [m^3]	Land occupation [m^2.org.arable]
Transportation										
Transport, lorry >16t, fleet average	tkm	ecoinvent 2.1	0.126	0.137	0.0465	0.122	2.13	2.15	0.168	0.00109
Transport, transoceanic freight ship	tkm	ecoinvent 2.1	0.012	0.023	0.0021	0.011	0.168	0.170	0.163	3.84e-5
Transport, freight, rail, diesel	tkm	ecoinvent 2.1	0.0497	0.0769	0.0100	0.0492	0.753	0.763	0.0789	9.05e-4
Transport, lorry >32t, EURO3	tkm	ecoinvent 2.1	0.117	0.107	0.0408	0.114	1.97	1.99	0.140	8.41e-4
Transport, lorry 16-32t, EURO3	tkm	ecoinvent 2.1	0.168	0.151	0.0658	0.164	2.78	2.80	0.215	0.00156
Transport, lorry 7.5-16t, EURO3	tkm	ecoinvent 2.1	0.292	0.262	0.0724	0.284	4.67	4.71	0.330	0.00266
Transport, lorry 3.5-7.5t, EURO3	tkm	ecoinvent 2.1	0.660	0.593	0.205	0.641	10.7	10.8	0.981	0.00846

Table 39 Unit process quality levels used in pedigree matrix analysis. Quality levels shown in order for reliability, completeness, temporal correlation, geographic correlation, further technological correlation, and sample size; basic uncertainty factors are also included.

	Airblade™		XLERATOR®, standard dryer, paper towels		Cotton roll towels	
Unit process	**Quality levels**	**GSD**	**Quality levels**	**GSD**	**Quality levels**	**GSD**
Materials						
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Adhesive for metals, at plant	1, 1, 3, 1, 3, 5, 1.05	1.322	—	—	—	—
Aluminium, primary, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Aluminium, secondary, from old scrap, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Ceramic tiles, at regional storage	—	—	2, 3, 3, 1, 3, 5, 1.05	1.333	—	—
Chromium, at regional storage	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Copper, primary, at refinery	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Cotton fibres, ginned, at farm (China)	—	—	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249
Electronic component, active, unspecified, at plant	—	—	2, 3, 3, 1, 3, 5, 1.05	1.333	—	—
Epoxy resin, liquid, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Galvanized steel	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Glass fiber reinforced polypropylene	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Glass fibre reinforced plastic, polyamide, injection moulding, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Glass fibre, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Melamine, at plant	1, 1, 3, 1, 3, 5, 1.05	1.322	—	—	—	—
Nickel, 99.5%, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Nylon 6, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Paper, newsprint, at regional storage	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Plastic mixture with extrusion	—	—	2, 3, 3, 1, 3, 5, 1.05	1.333	—	—
Polycarbonate / Acrylonitrile-butadiene-styrene	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Polyethylene, LDPE, granulate, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Polyethylene terephthalate, granulate, amorphous, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Polypropylene, granulate, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Polystyrene, general purpose, GPPS, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Polyurethane, rigid foam, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—

	Airblade™		XLERATOR®, standard dryer, paper towels		Cotton roll towels	
Unit process	**Quality levels**	**GSD**	**Quality levels**	**GSD**	**Quality levels**	**GSD**
Materials (cont'd)						
Polyvinylchloride, at regional storage	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Stainless steel sheet	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Steel, converter, chromium steel 18/8, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Sulphate pulp, ECF bleached, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Pulp from waste paper	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Synthetic rubber, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Zinc, primary, at regional storage	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Printed wiring board, through-hole, lead-free surface, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—	—	—
Sawn timber, softwood, planed, kiln dried, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Corrugated board, fresh fibre, single wall, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Corrugated board, recycling fibre, single wall, at plant	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Packaging film, LDPE, at plant	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Manufacturing						
Electricity, medium voltage, at grid (China)	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Electricity, medium voltage, at grid (US)	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Natural gas, burned in industrial furnace low-NOx >100kW	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Water, unspecified natural origin	1, 1, 3, 1, 1, 5, 1.05	1.235	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Treatment, sewage, to wastewater treatment, class 3	1, 1, 3, 1, 1, 5, 1.05	1.235	1, 1, 3, 1, 1, 5, 1.05	1.235	—	—
Extrusion, plastic film	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Extrusion, plastic pipes	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249	—	—
Spinning cotton fiber	—	—	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249
Sizing	—	—	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249
Weaving	—	—	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249
De-sizing / scouring / bleaching	—	—	—	—	2, 3, 3, 1, 1, 5, 1.05	1.249
Use						
Electricity, low voltage, at grid (US)	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 3, 1, 5, 1.05	1.25
Laundering	—	—	—	—	2, 3, 3, 3, 1, 5, 1.05	1.25

	Airblade™		XLERATOR®, standard dryer, paper towels		Cotton roll towels	
Unit process	**Quality levels**	**GSD**	**Quality levels**	**GSD**	**Quality levels**	**GSD**
End-of-life						
Recycling cardboard	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Disposal, municipal solid waste, to landfill, methane energy recovery	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Disposal, municipal solid waste, to incineration, energy recovery	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Transportation						
Transport, lorry >16t, fleet average	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067
Transport, transoceanic freight ship	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Transport, freight, rail, diesel	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249	2, 3, 3, 1, 1, 5, 1.05	1.249
Transport, lorry >32t, EURO3	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067
Transport, lorry 16-32t, EURO3	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067
Transport, lorry 3.5-7.5t, EURO3	—	—	—	—	2, 3, 3, 3, 1, 5, 2	2.068
Transport, lorry 7.5-16t, EURO3	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067	2, 3, 3, 1, 1, 5, 2	2.067

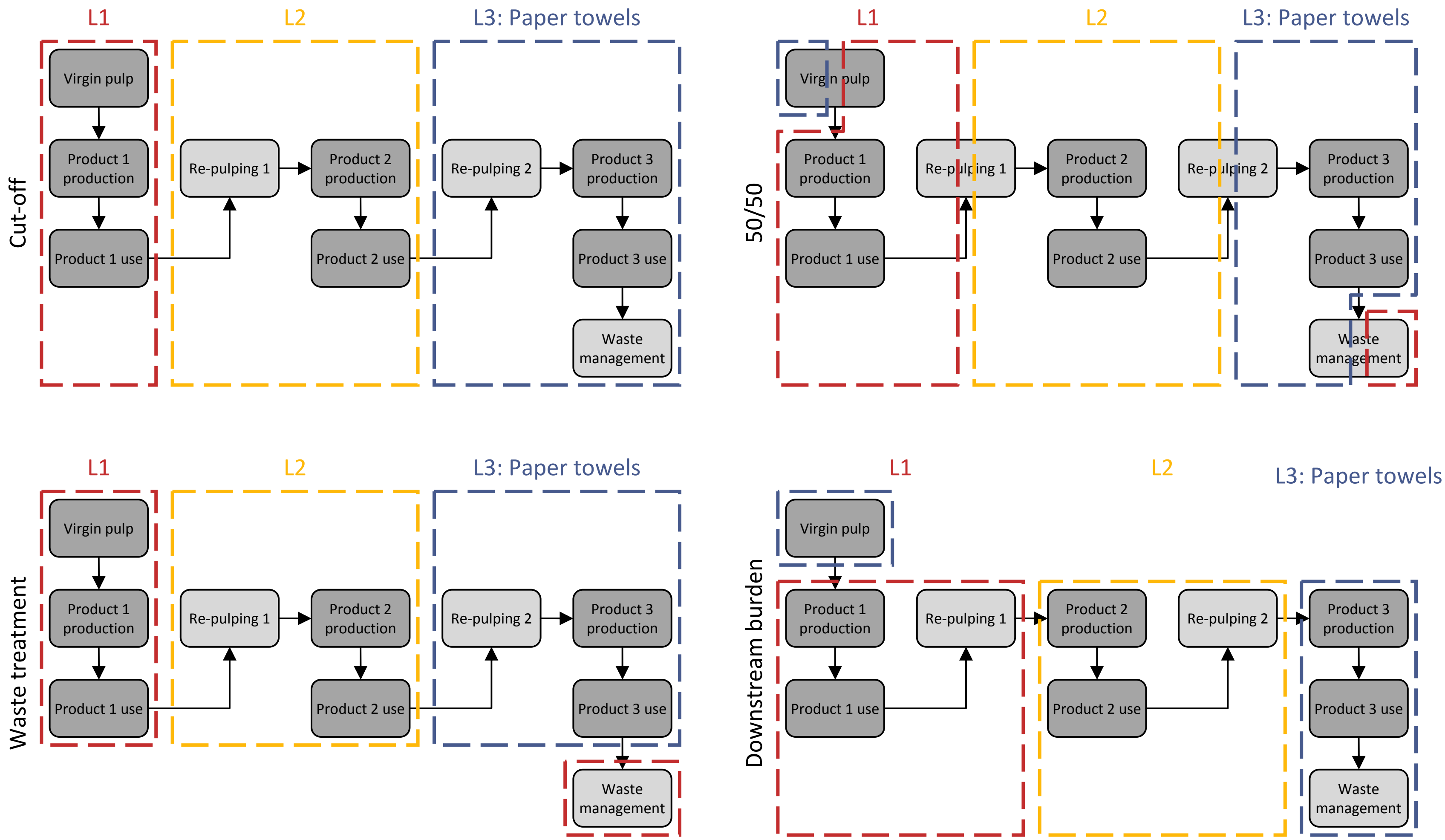

Figure 36 Allocation schemes for recycled content [60].

A.4 Allocation of recycled content

When a product is part of an open loop recycling system, a methodological decision has to be made regarding how to allocate the burdens from virgin material production, recycled material production, and disposal at end-of-life. A number of options have been proposed (see [60]), some of which are illustrated in Figure 36 and used in a sensitivity analysis in this report. Three product life cycles, L1, L2, and L3, were chosen for each system to approximately represent the number of times paper is used and reused in the US before being sent to a landfill or an incinerator. This assumption is consistent with the assumption made by the Environmental Paper Network's Paper Calculator [31]; it can also be estimated by calculating based on US paper and paperboard recycling rates[3]. Since paper towels are always disposed of after use, they represent L3, the final life cycle in the open loop system.

A fifth allocation scheme based on ISO 14049 [61] is also considered. In the ISO-based scheme, L2 and L3 are assigned the full burden of their preceding repulping steps—similar to the cut-off scheme in Figure 36—as well as some fraction of the burden of pulp manufactured from virgin content. The allocation of the virgin pulp is based on the production, disposal, and recycling losses incurred over each life cycle. Figure 37 illustrates the flow of pulp through an open loop recycling system. For this study, a 3.9% production loss [14], a 44.5% disposal loss [30], and a 33.3% recycling loss [12] are assumed. Thus, in order to produce 1 kg of paper towels, 8.2 kg of virgin pulp is required. This 8.2-kg of material is allocated to the three life cycles as follows:

$$\text{L1 burden} = 8.2\ \text{kg} \cdot \left(0.039 + 0.428 + \frac{0.533}{3}\right) = 5.3\ \text{kg}$$

$$\text{L2 burden} = 8.2\ \text{kg} \cdot \left(0.014 + 0.152 + 0.177 + \frac{0.19}{2}\right) \cdot \frac{2}{3} = 2.4\ \text{kg}$$

$$\text{L3 burden} = 8.2\ \text{kg} \cdot \left(\frac{0.19}{2}\right) \cdot \frac{2}{3} = 0.5\ \text{kg}$$

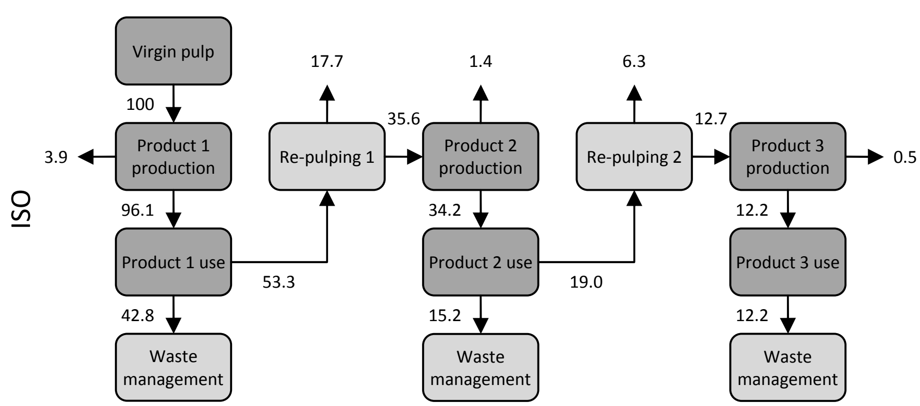

Figure 37 Material flow through an open loop paper recycling system.

[3] In 2008, 55.5% of paper and paperboard were recycled [30]. This corresponds to 2.24 product life cycles, based on the sum of an infinite geometric series.

A.5 NSF P335 Protocol

The NSF P335 Protocol "contains minimum requirements for materials, design and construction, and performance of commercial hand dryers that incorporate antimicrobial capabilities in their design and function" [19]. The protocol specifies a test procedure for determining the length of time a hand dryer requires to hygienically dry a pair of hands. Six subjects with hands of a specific size are selected. The subjects wet and then dry their hands in a hand dryer as per manufacturers' instructions for set periods of time (increments of 5 seconds). Any moisture remaining on their hands is subsequently removed with a paper towel, which is weighed immediately afterwards to assess the exact amount of water left behind. The procedure is repeated until the time it takes to reach 0.1 g of moisture can be extrapolated for each hand dryer type.

A.6 Comparison with existing studies

Existing hand dryer and towel life cycle assessments are reviewed and their results compared with results from this study. The intention of this section is to provide a "reality check" on the numbers generated in this analysis. Existing LCAs used numerous assumptions that are different than the ones used in this study. Indeed, the differences are the motivation for this study. Thus, one would expect the results of existing studies to be different from the results from this analysis depending on the variation in assumptions. However, a comparison of the results from existing studies and this study help to insure that this study's results are reasonable and that the differences in results can be explained by the differences in assumptions.

Global warming potential is chosen as the comparison metric because most studies use this metric to report environmental impact. The characterization factors, however, differ slightly across studies because a few of the studies were conducted prior to 2007, the year of the fourth IPCC report in which these factors were updated.

A.6.1 Dryers

Figure 38 compares hand dryer GWP, calculated with reported dry times, with corresponding results from the Excel Dryer [14], AirDri [6], MyClimate [7], and Carbon Trust [27] studies. If necessary, results from the published studies are normalized by the functional unit in those studies to represent the impact of drying one pair of hands. In some instances, the GWP associated with each dryer type is comparable across the studies, particularly for the Excel Dryer results. The different results can generally be attributed to differing assumptions. For example, the lower GWP of the dryers in the MyClimate study [7] can be attributed to the study's use of 10- and 27-second dry times for the Dyson Airblade™ hand dryer and the standard dryer, respectively, combined with the Swiss average electric grid mix, which has much lower emissions compared to the US average grid mix[4]. The differences are much smaller for the XLERATOR® results and can be attributed to the difference in versions of ecoinvent libraries (v2.1 used by this study, v2.01 used by the study for Excel Dryer), the assumption that manufacturing takes place in China rather than the US, and the inclusion of standby energy consumption in the use stage of the life cycle. Similar factors also contribute to the differences between standard

[4] Electricity in Switzerland is generated primarily from hydropower and nuclear sources [54]; consequently, grid emissions are around 16% of US emissions per unit of electricity.

dryer GWPs. Not enough information is available in the Carbon Trust and Airdri reports to explain why their respective GWPs of the Airblade™ and standard dryers are lower than this study's results. Despite the use stage being the impact driver, neither provides details on electric grid mix or emission factors.

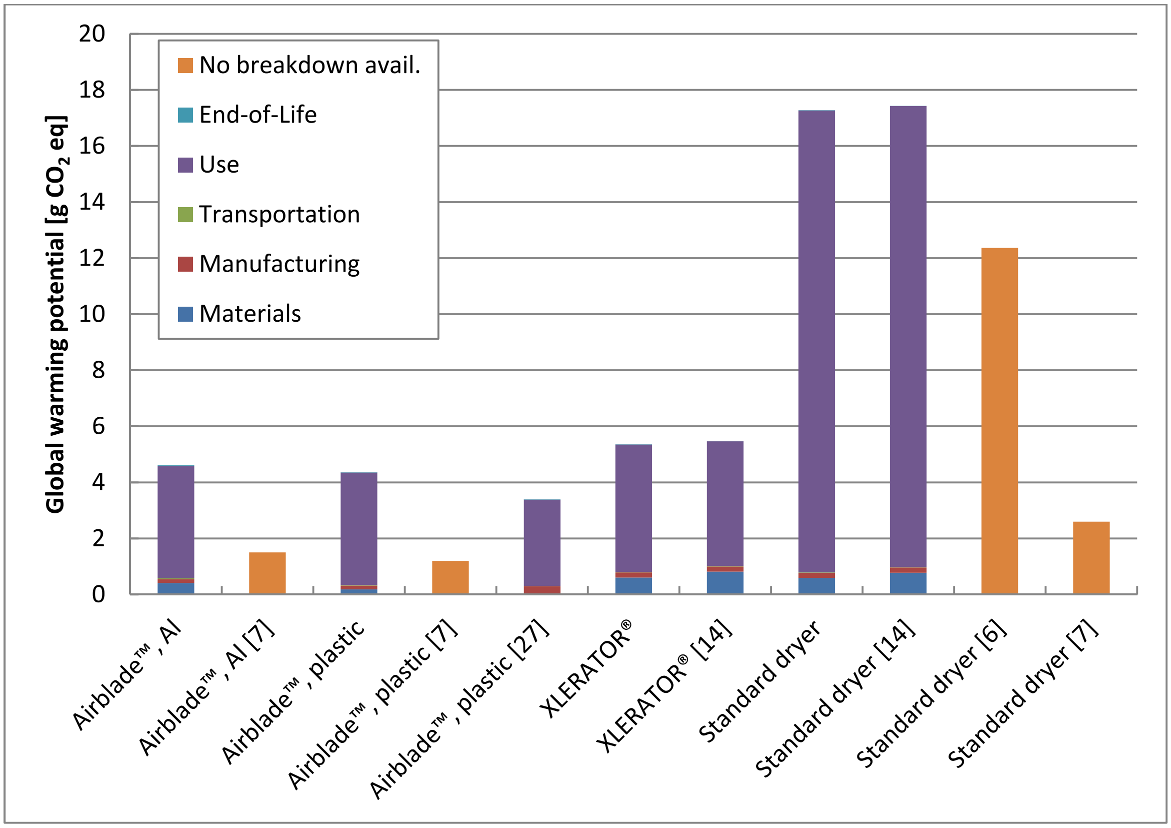

Figure 38 Comparison of dryer GWP (calculated using reported dry times) with results from literature.

A.6.2 Cotton roll towels

Figure 39 compares the cotton roll towel GWP calculated in this report with results from the ETSA [12] and MyClimate [7] studies. As with the dryers, a number of the differences between results can be attributed to the differing assumptions between the studies. For instance, the impact from cotton towel production (materials plus manufacturing) is lower in the ETSA study than in this study, not only because of the different unit process databases—Umberto v4.3 in the ETSA study versus ecoinvent v2.1 in this study—used by the two studies, but also because of the different assumptions for cotton fiber production. The difference in transportation is also likely due to the use of different transportation processes from different databases. Towel manufacturing input and output flows, though, are the same (cotton towel manufacturing processes in Appendix A.2 are based on Section 7.2 in [12]). The impact of washing, however, is similar for both analyses. Although the ETSA study contains a detailed breakdown of chemicals found in detergent, most of the impact comes from natural gas and electricity, the flows of which are the same in both studies. Finally, ETSA assumes that 88% of cotton towels are recycled as disposable industrial cleaning cloths and displace virgin paper towels, and that cotton towels are incinerated with energy recovery—both of which lead to a negative end-of-life impact.

While there are minimal details on the MyClimate study, the report indicates that the majority of a cotton towel's impact is from washing, which is consistent with both this and ETSA results.

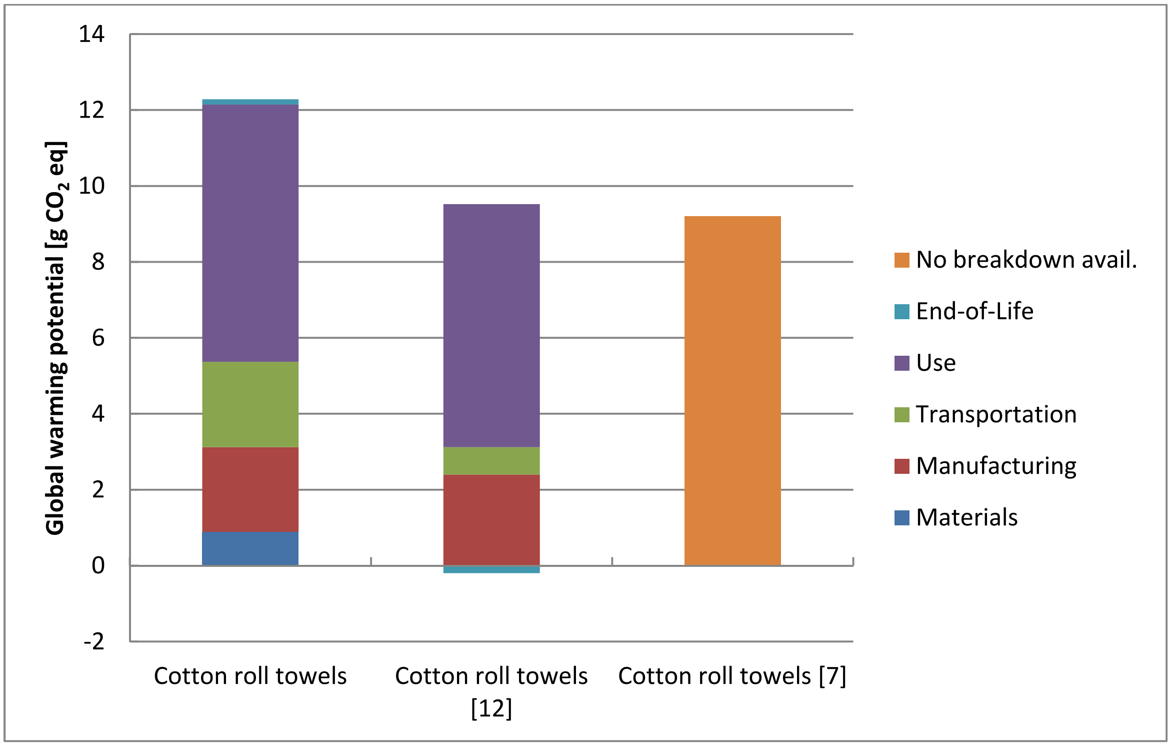

Figure 39 Comparison of cotton roll towel GWP with results from literature.

A.6.3 Paper towels

Although results in this study indicate that using recycled content can reduce a paper towel's production burden, this conclusion ultimately depends on the assumptions that go into calculating impact as well as the selected LCIA methodology. Figure 40 compares paper towel GWP from different studies. Study assumptions are summarized in Table 40. As with the previous two systems, the numbers are normalized by functional unit to represent the impact for drying one pair of hands. The literature results show that in some cases, virgin paper towels have the greater burden [7, 14] while in others, paper towels with recycled content have a higher impact [12, 13]. The Excel study [14], for instance, concludes that virgin paper towels have the higher impact because, due to lack of data, it does not account for the energy required to convert waste paper into pulp. It does, however, address this assumption in its sensitivity analysis by adding the energy required for re-pulping to the life cycle inventory, thus increasing the impact of the recycled content in the paper towels (represented by "Recycled 100% a [14]" in Figure 40). Likewise, the Kimberly-Clark study examines two different allocations of recycled content ("Recycled 45% [13]" and "Recycled 45% a [13]" in the figures). Although the study concludes that paper towels with recycled content have a greater impact than those with virgin content, the choice of allocation scheme makes a difference.

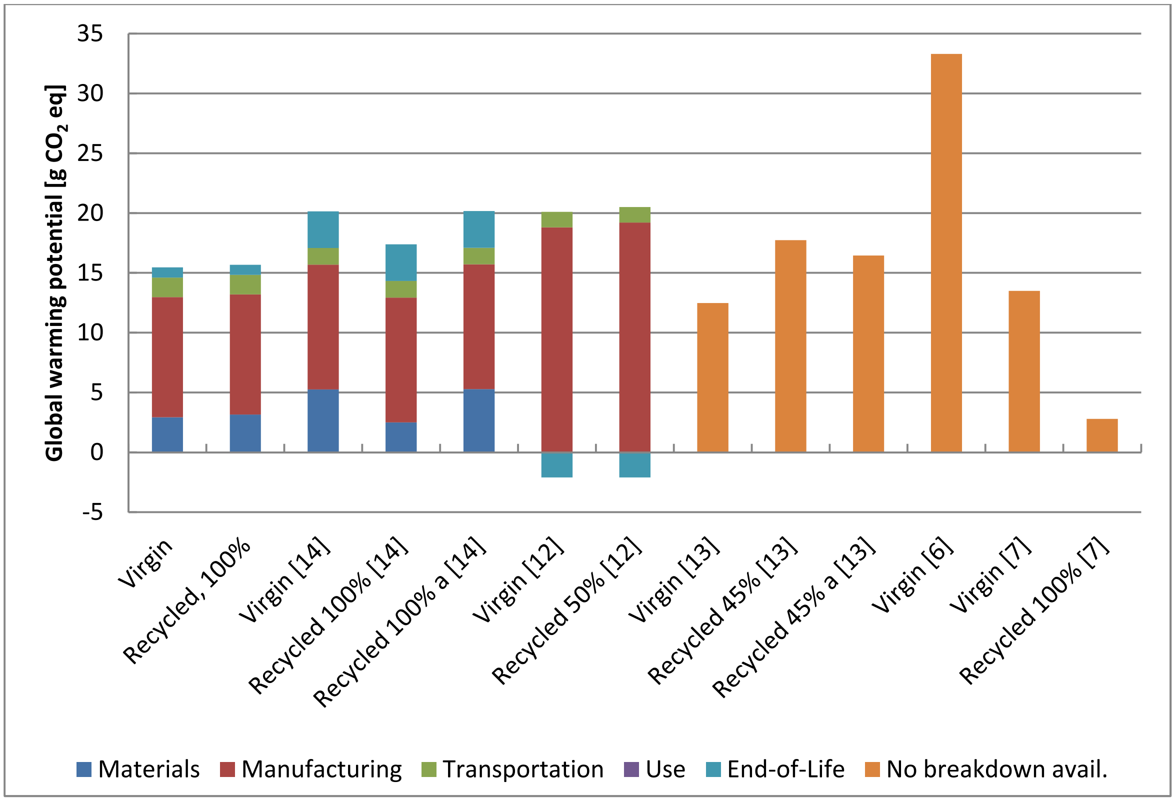

Figure 40 Comparison of paper towel system GWP with results from literature.

While the studies do consistently conclude that the materials and manufacturing stages contribute the most to total paper towel system impact, differences in assumptions lead to variation in system impact. As Table 40 indicates, the studies assume that different numbers of paper towels, with different masses, are required to dry a pair of hands. Dispensers and waste bins are not always included in the analysis, nor is energy recovery from incineration. Additionally, databases and LCIA methodologies differ. While all the studies calculate GWP over a 100-year time frame, only some are recent enough to use the updated IPCC 2007 methodology.

Since most of a paper towel's burden lies in production, it is important that the assumptions associated with these life cycle stages are reasonable. One key assumption in this study was the adoption of the ECF-bleached sulfate pulping process as a proxy for the manufacture of deinked pulp. In the modified process, 1.5 kg of waste paper was directly substituted for the 4,108 cm^3 of wood required per kilogram of recycled pulp. The assumption is now assessed by comparing the modified process with processes from the Excel [14] and ETSA [12] studies (Figures 41 and 42). Literature results were recalculated to place them on a consistent basis—at least in terms of ecoinvent database and LCIA methodology—with this study. The figures indicate that this study's assumptions are reasonable given that results are more or less consistent with those of other studies. GWP results from the ETSA study are slightly higher because the unit process inventory does not specify whether carbon dioxide emissions are from fossil or biogenic sources. The distinction between these two sources is also the reason why in Figure 41, a kilogram of tissue has approximately the same GWP regardless of whether it uses virgin or recycled content, whereas in Figure 42, the CED of tissue manufactured from virgin content is consistently higher than the CED of tissue from recycled content. CED accounts for the energy embodied in the virgin wood, whereas GWP does not account for carbon stored in solids or biogenic carbon dioxide and carbon monoxide emissions.

Table 40 Comparison of assumptions for paper towel systems from literature.

	MIT / Dyson	Excel [14]	ETSA [12]	KC [13]	Airdri [6]	MyClimate [7]
Functional Unit [pairs of hands]	1	260,000	10,000	39,000	130,000	1
Towels per functional unit [#]	2	2	2	1.5	2	3 or 2
Towel mass [g per towel]	1.98 g	1.98 g	4 g	1.98 g	3.79 g	2.6 g or N/A
Recycled content	0%, 100%	0%, 100%	0%, 50%	0%, 45%	0%	0%, 100%
Manufacturing location	US	US	EU	North America	EU	Switzerland, Germany
Use location	US	US	EU	US	EU	Switzerland, EU
Dispenser?	Y	Y	N	N	Y	N
Waste bin?	Y	Y	N	N	Y	N
Liners?	Y	Y	Y	N	Y	N
Packaging?	Y	Y	N	Y	Y	Y
Recycling allocation	50/50	Cut-off	Cut-off	Cut-off, ISO	N/A	Not specified
Incineration fraction	19%	20%	100%	21%	Not specified	Not specified
Energy recovery?	N	Y	Y	N	Not specified	Not specified
Database	ecoinvent v2.1	ecoinvent v2.01	Umberto v4.3	ecoinvent, own data	PEMS4	ecoinvent v2.0
GWP methodology	IPCC 2007 100a	IPCC 2007 100a	100-yr	IPCC 2007 100a	IPCC 2001	IPCC 2001

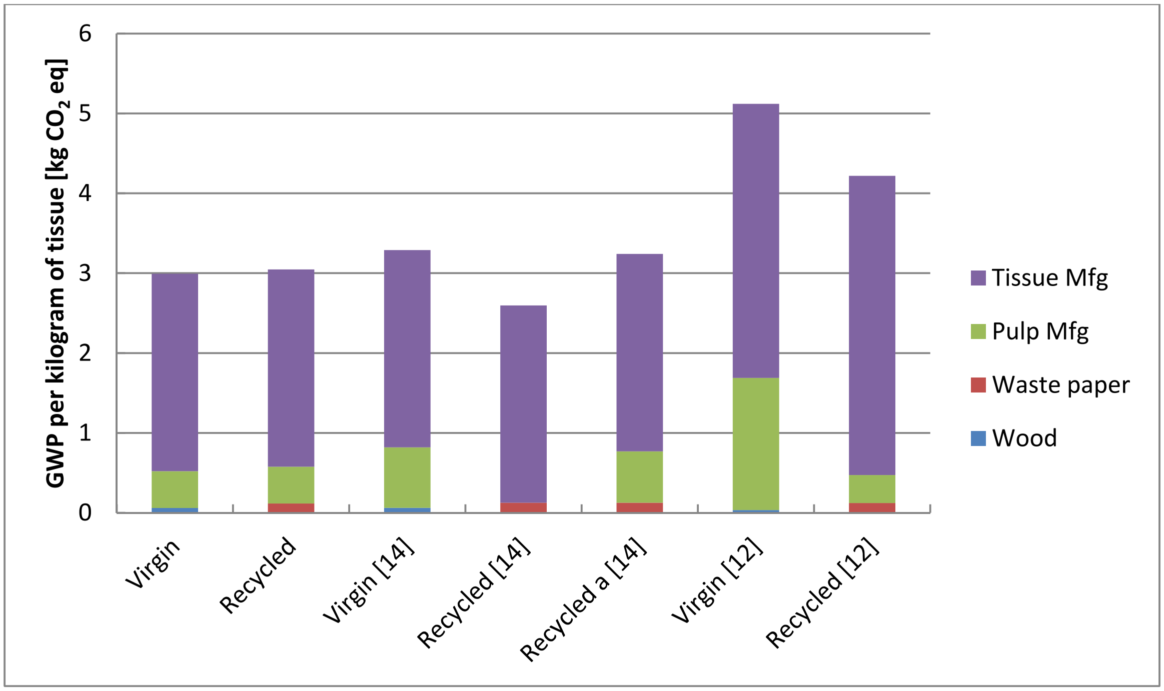

Figure 41 Comparison of GWPs resulting from the production of one kilogram of tissue.

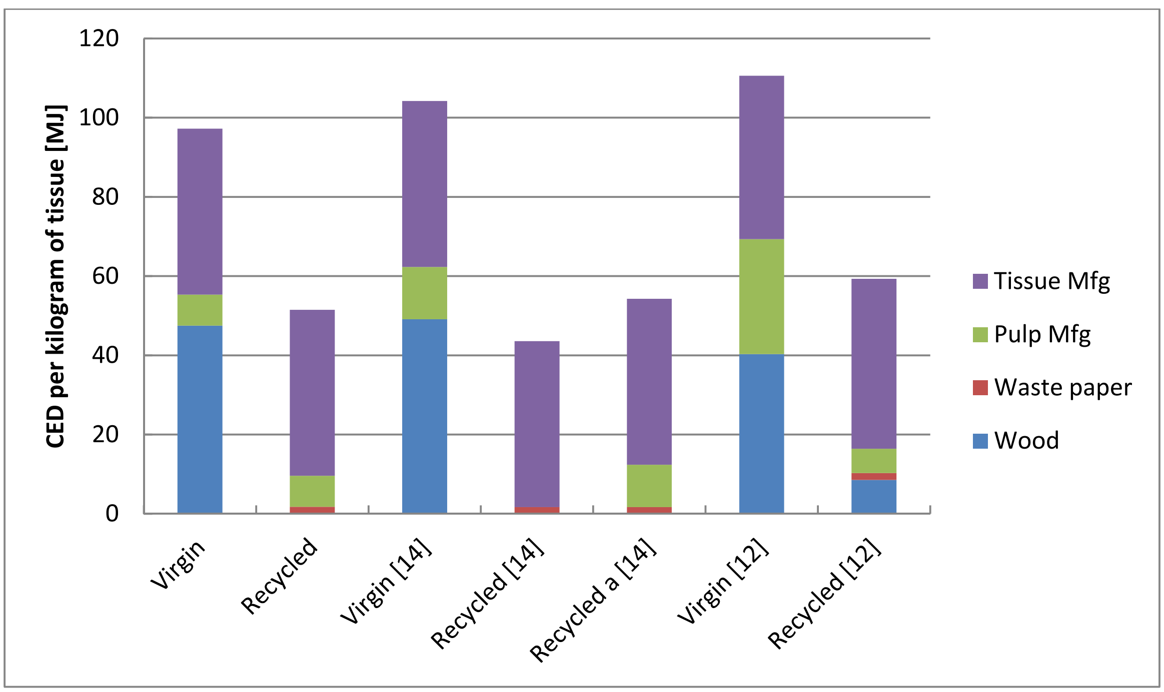

Figure 42 Comparison of CEDs resulting from the production of one kilogram of tissue.

A.7 Supplemental analyses

A.7.1 Warehousing

This section supports the claim, stated in Section 2.2.2.1, that warehousing can justifiably be excluded from this study's scope. Rough calculations, based on data from CMU's buy.com study [28], predict that warehousing accounts for less than 4% of drying system overall impact. These calculations assume that warehousing results in emissions of 675 g CO2 eq per package. Each package, in turn, contains one dryer, 2,400 paper towels, or 100 cotton roll towel pulls, which are respectively capable of drying 350,000, 1,200, or 10,000 pairs of hands. Since one pair of hands represents a functional unit (FU), the emissions can be normalized by the number of pairs of hands and used to calculate the warehouse's contribution to a functional unit's GWP. The results in Table 41 indicate that the paper towels are most affected when warehousing is included in the analysis.

The analysis can be further refined by acknowledging that economic data was first used to allocate warehouse emissions to buy.com before being normalized by the number of packages buy.com sold. One dryer is clearly more expensive than one box of paper towels and thus will be allocated a greater fraction of the warehouse's environmental impact. Going by the costs in Table 41, one dryer should be allocated the same burden as 40 boxes of paper towels. While this will reduce paper towel warehousing burden, both relative to the dryer's impact and to total system impact, the result will still be higher than that of the dryer.

Table 41 Warehousing impact assumptions.

Package unit	One dryer	One box of paper towels	One roll of cotton towels
Package contents	1 dryer	2,400 towelsa	100 pullsb
Pairs of hands	350,000	1,200	10,000
GWP [g CO2 eq / pkg]	675	675	675
GWP [g CO2 eq / FU]	0.002	0.56	0.068
Fraction of total GWP	0.04%	3.1%	0.56%
Cost	$1,200c	$30	?

(a) Based on Kimberly-Clark 01510 c-fold towels

(b) ETSA study [12]

(c) Cost of Dyson Airblade™ hand dryer.

A.7.2 Regional variation: secondary locations

In addition to the regions analyzed in Section 5.1.11, a number of secondary regions are also evaluated. Table 42 details assumptions used in the analysis. As before, transportation, grid mix, use intensity, dryer power rating, and end-of-life scenario are all adjusted to account for the difference between territories (although recycling scenarios are not considered for end-of-life). Results are listed in Table 43 for GWP, CED, Human Health, and Ecosystem Quality (the latter two representing two of the four IMPACT 2002+ endpoint categories).

Table 42 Regional assumptions for secondary regions.

	Austria	Belgium	Denmark	Italy	Netherlands	Spain	Refs
Transportation							
Port A to B	19,625 km	19,625 km	19,625 km	19,625 km	19,625 km	19,625 km	[27, 43]
Port B to warehouse	30 km	30 km	30 km	30 km	30 km	30 km	
Warehouse to washroom	814 km	538 km	1,030 km	1,252 km	604 km	1,732 km	
Grid mix							
Coal	20%	10%	41%	13%	26%	27%	[32]
Oil	2%	2%	4%	13%	3%	8%	
Natural gas	16%	24%	21%	39%	54%	19%	
Nuclear	6%	53%	6%	6%	7%	24%	
Renewable[a]	53%	4%	23%	21%	5%	20%	
Use intensity[b]							
Airblade™	10 sec	10 sec	10 sec	10 sec	10 sec	10 sec	[12, 14, 27]
XLERATOR®	18 sec	18 sec	18 sec	18 sec	18 sec	18 sec	
Standard dryer	28 sec	28 sec	28 sec	28 sec	28 sec	28 sec	
Cotton roll towels	1 towel	1 towel	1 towel	1 towel	1 towel	1 towel	
Paper towels	2 towels	2 towels	2 towels	2 towels	2 towels	2 towels	
Dryer power rating							
Airblade™	1,600 W	1,600 W	1,600 W	1,600 W	1,600 W	1,600 W	[27]
XLERATOR®	1,400 W	1,400 W	1,400 W	1,400 W	1,400 W	1,400 W	
Standard dryer	2,400 W	2,400 W	2,400 W	2,400 W	2,400 W	2,400 W	
MSW							
Cardboard recycled	67%	60%	70%	69%	69%	51%	[54]
Incinerated	10%	34%	—	13%	21%	1%	
Incinerated w/ recovery	24%	39%	76%	6%	8%	4%	
Landfilled w/ CH_4 capture	66%	27%	24%	81%	61%	95%	

	Sweden	Switzerland	Australia	Canada	Saudi Arabia	United Arab Emirates	Refs
Transportation							
Port A to B	19,625 km	19,625 km	8,290 km	9,330 km	10,780 km	10,780 km	[27, 43, 62]
Port B to warehouse	30 km	30 km	19 km	3,381 km	0 km	940 km	
Warehouse to washroom	1,679 km	389 km	1,019 km	571 km	1,175 km	175 km	
Grid mix							
Coal	1%	6%	77%	17%	57%	2%	[32, 53]
Oil	1%	—	1%	2%	43%	98%	
Natural gas	1%	2%	15%	6%	—	—	
Nuclear	46%	49%	—	14%	—	—	
Renewable[a]	41%	37%	7%	60%	—	—	
Use intensity[b]							
Airblade™	10 sec	10 sec	10 sec[c]	12 sec[c]	10 sec[c]	10 sec[c]	[12, 14, 27]
XLERATOR®	18 sec	18 sec	18 sec	20 sec	18 sec	18 sec	
Standard dryer	28 sec	28 sec	28 sec	31 sec	28 sec	28 sec	
Cotton roll towels	1 towel	1 towel	1 towel	1 towel	1 towel	1 towel	
Paper towels	2 towels	2 towels	2 towels	2 towels	2 towels	2 towels	
Dryer power rating							
Airblade™	1,600 W	1,600 W	1,600 W	1,400 W	1,600 W	1,600 W	[27]
XLERATOR®	1,400 W	1,400 W	1,400 W	1,500 W	1,400 W	1,400 W	
Standard dryer	2,400 W	2,400 W	2,400 W	2,300 W	2,400 W	2,400 W	
MSW							
Cardboard recycled	12%	50%	40%	21%	—	—	[54, 63-65]
Incinerated	—	—	—	5%	—	—	
Incinerated w/ recovery	12%	100%	—	—	—	—	
Landfilled w/ CH_4 capture	88%	—	100%	95%	100%[d]	100%[d]	

(a) Renewable includes electricity produced from hydropower, solar, wind, and cogen

(b) Dryer use intensity measured according to the NSF Protocol P335 [19]

(c) Use intensity in Canada assumed to be the same as in the US; use intensity in Australia, Saudi Arabia and UAE assumed to be the same as in the EU (based on country grid voltages)

(d) Estimated

Table 43 Secondary region impact results.

	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels, virgin	Paper towels, 100% recy.
Global warming potential [g CO_2 eq]							
Austria	2.60	2.37	4.09	9.29	10.3	11.9	12.1
Belgium	2.25	2.02	3.52	7.82	10.2	11.7	11.9
Denmark	3.42	3.18	5.40	12.7	10.6	13.7	14.0
Italy	3.51	3.28	5.56	13.1	10.6	13.6	13.9
Netherlands	3.89	3.66	6.18	14.7	10.7	14.1	14.3
Spain	3.29	3.06	5.20	12.2	10.5	13.2	13.5
Sweden	1.05	0.81	1.56	2.74	9.7	9.7	10.0
Switzerland	1.19	0.96	1.80	3.36	9.8	9.7	10.0
Australia	6.31	6.08	10.1	24.9	11.5	17.0	17.2
Canada	2.16	1.92	3.69	7.49	10.1	10.5	10.7
Saudi Arabia	5.64	5.41	9.03	22.1	11.3	16.1	16.3
United Arab Emirates	5.75	5.52	9.20	22.6	11.3	15.6	15.8
Cumulative energy demand [kJ]							
Austria	49.8	46.2	79.6	186	185	393	205
Belgium	65.4	61.8	105	252	190	412	224
Denmark	56.7	53.1	91.0	216	186	388	200
Italy	57.7	54.0	92.2	219	188	418	230
Netherlands	63.0	59.3	102	241	190	421	233
Spain	64.5	60.8	103	247	191	434	246
Sweden	57.4	53.7	91.5	217	188	424	236
Switzerland	56.5	52.9	90.7	215	185	369	181
Australia	75.4	71.7	121	293	194	442	254
Canada	53.3	49.6	94.2	202	186	399	210
Saudi Arabia	86.2	82.6	139	339	198	458	269
United Arab Emirates	95.0	91.3	153	376	201	461	273

	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels, virgin	Paper towels, 100% recy.
IMPACT 2002+ Human Health [10^{-9} DALY]							
Austria	1.21	1.03	1.81	3.44	5.90	7.36	7.50
Belgium	1.41	1.24	2.14	4.29	5.98	7.81	7.95
Denmark	1.62	1.45	2.49	5.20	6.04	8.00	8.14
Italy	1.98	1.81	3.07	6.70	6.19	8.99	9.13
Netherlands	1.51	1.34	2.31	4.74	6.01	7.94	8.08
Spain	3.22	3.05	5.07	11.9	6.63	11.1	11.2
Sweden	1.33	1.15	2.00	3.92	5.96	8.09	8.23
Switzerland	0.95	0.78	1.40	2.38	5.78	6.41	6.55
Australia	4.31	4.14	6.85	16.5	6.96	12.06	12.2
Canada	1.81	1.64	3.05	6.03	6.09	7.99	8.13
Saudi Arabia	5.73	5.56	9.16	22.5	7.47	14.3	14.4
United Arab Emirates	1.59	1.42	2.44	5.09	6.00	7.39	7.53
IMPACT 2002+ Ecosystem Quality [PDF.cm^2.yr]							
Austria	6.18	5.79	12.7	24.7	48.4	76.2	30.0
Belgium	7.12	6.73	14.2	28.7	48.7	76.6	30.4
Denmark	7.87	7.48	15.4	31.9	48.9	77.1	31.0
Italy	7.51	7.11	14.8	30.2	49.0	80.4	34.2
Netherlands	7.68	7.28	15.1	31.0	48.9	79.0	32.8
Spain	8.46	8.06	16.3	34.1	49.3	83.5	37.3
Sweden	7.56	7.15	14.8	30.3	49.0	82.3	36.1
Switzerland	6.14	5.76	12.7	24.8	48.1	71.5	25.4
Australia	12.6	12.2	23.0	51.4	50.7	88.1	42.0
Canada	7.48	7.08	16.1	30.4	48.8	78.2	32.1
Saudi Arabia	16.5	16.2	29.5	68.3	52.1	93.3	47.2
United Arab Emirates	7.08	6.69	14.1	28.5	48.7	77.2	31.0

A.8 Evaluation

The evaluation, required in the ISO standards, consists of checks performed on the data and on the results of the analysis. These checks ensure the data is complete and consistent, both among the product systems and with the goal and scope of the analysis, and assess the sensitivity of the results to variation in the data and other methodological decisions.

A.8.1 Completeness check

The completeness check summarizes available data for each product system and life cycle stage. Data gaps are identified and the information is reviewed for consistency with the goal and scope of the analysis. Completeness is detailed in Table 44. In some cases, steps were taken to accommodate incomplete data. For instance, a generic unit process ("Electronic component, active, unspecified") was used for the optics and control assemblies in the XLERATOR® and standard dryer inventories due to lack of more detailed information regarding these components. Since it was shown to account for over 50% of dryer production burden (see Figures 13 and 14), however, a sensitivity analysis was conducted in which a more specific unit process, "Printed wiring board, through-hole, lead-free surface," was substituted (Section 5.1.6). The uncertainty analyses in Section 0 take the change of unit process into account as well. Additionally, appropriate unit process inventory data for pulp manufactured from waste paper (i.e. deinked pulp) could not be identified. This lack of information was addressed by using the inventory for manufacturing ECF-bleached sulfate pulp as a proxy for manufacturing deinked pulp with waste paper substituted in place of wood. A consistency check was performed with other literature results for paper towel production (see Figure 40) to ensure that this study's results were reasonable; however, it is recommended that a more detailed study on recycled paper towels be conducted.

In other instances, the missing information is shown or anticipated to have minimal effect on the final environmental impact results. In the case of the XLERATOR® dryer's use stage, the dryer's standby power rating was unavailable and that of the Dyson Airblade™ hand dryer substituted in its place. Figure 15 illustrates, however, that the substitution has minimal impact on overall results because standby energy consumption accounts for a very small fraction of use stage energy consumption. While additional information was available on chemically disinfecting the cotton roll towels during their use phase, this information was not used due to lack of unit process inventory data. Instead, the unit process for "Soap" was used in place of all the chemicals (i.e. laundry detergent) listed in the ETSA report [12] and the results checked against literature (see Figure 39). Finally, energy or additional inputs required to manufacture dryer or towel packaging were only separated out for the Dyson Airblade™ hand dryers and is unknown whether such information was accounted for in the product system bills of activities. Packaging, however, is a small fraction of total burden (see Figure 11) so the missing information is not anticipated to affect the study's conclusions.

Table 44 Summary of drying system data completeness.

Life cycle stage	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels, virgin	Paper towels, recycled
Materials	Available, complete	Available, complete	Available	Available	Available, complete	Available, complete	Available
Manufacturing	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete
Use	Available, complete	Available, complete	Available	Available, complete	Available	N/A	N/A
End-of-life	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete
Transportation	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete	Available, complete
Packaging	Available, complete	Available, complete	Available	Available	Available	Available	Available
Dispenser	N/A	N/A	N/A	N/A	Available, complete	Available, complete	Available, complete
Waste bin and liners	N/A	N/A	N/A	N/A	N/A	Available, complete	Available, complete

A.8.2 Sensitivity check

The sensitivity check assesses and summarizes the reliability of the final results given uncertainties in the data, variations in the assumptions and methods, and choices of LCIA methodology. Key issues that drive variation in the results are also identified. Since the evaluation of environmental impact under different scenarios is one of this study's goals, sensitivity and uncertainty analyses were conducted and presented as part of the report (Sections 5.1 and 0). This check relies on results from those analyses, as well as results from Section 4.2, the baseline scenario analysis.

Table 45 explores how changing the life cycle impact assessment methodology impacts the comparison among drying systems. Results are shown relative to the impact of the aluminum Dyson Airblade™ hand dryer. The results indicate that the impact of the plastic Dyson Airblade™ hand dryer is consistently lower than that of the aluminum Dyson Airblade™ hand dryer, and that the impacts of the standard dryer and paper towels are, almost consistently, multiple times that of the Dyson Airblade™ hand dryers. The XLERATOR® and cotton roll towel systems generally fall in between these two extremes. Further discussion can be found in Section 6.3.

Table 45 Sensitivity to LCIA methodology (relative to aluminum Dyson Airblade™ hand dryer).

Life cycle stage	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels, virgin	Paper towels, recycled
Global warming potential	1.0	0.95	1.8	3.9	2.4	3.4	3.4
Human health, IMPACT 2002+	1.0	0.95	1.8	3.8	1.9	3.2	3.2
Ecosystem quality, IMPACT 2002+	1.0	0.96	2.1	4.1	4.8	8.2	3.7
Cumulative energy demand	1.0	0.95	1.8	3.9	2.6	5.9	3.4
Water consumption	1.0	0.69	1.3	2.8	0.64	1.6	1.6
Land occupation, IMPACT 2002+ midpt	1.0	0.92	2.2	4.7	220	440	21

Table 46 summarizes the sensitivity of drying system GWP to variation in baseline scenario assumptions. The column “Changes from baseline” indicates minimum and maximum percentage changes (when possible) in each attribute from the baseline; corresponding effects of these changes on drying system GWP are shown in the columns to the right. The results indicate that drying system impacts are most sensitive to changes in electric grid mix and use intensity. The GWPs of the Dyson Airblade™ hand dryers and XLERATOR® dryer are also sensitive to reduction in lifetime usage, which increases the fraction of hand dryer production burden allocated to the functional unit. Although hand-drying system impacts are also shown to be sensitive to use location, this sensitivity is primarily driven by changes in use phase electric grid mix.

Table 46 Summary of drying system GWP sensitivity to baseline scenario assumptions.

	Change from baseline		Airblade™, aluminum		Airblade™, plastic		XLERATOR®		Standard dryer		Cotton roll towels		Paper towels, virgin		Paper towels, recycled	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
Lifetime usage	-57%	+29%	+20%	-3.4%	+14%	-2.3%	+15%	-2.5%	+6.2%	-1.0%	+2.6%	-0.4%	+6.5%	-1.1%	+6.5%	-1.1%
Manufacturing electric grid mix	-98%[a]	+23%	-2.9%	+0.7%	-3.1%	+0.7%	-1.8%	+0.4%	-0.8%	+0.2%	-14%	+3.2%	-41%	+24%	-40%	+24%
Use electric grid mix	-98%[a]	+58%	-86%	+50%	-90%	+53%	-88%	+52%	-94%	+55%	-12%	+7.2%	—	—	—	—
Use intensity	-50%	+25% to +100%	-42%	+21%	-45%	+22%	-43%	+21%	-45%	+24%	—	+98%	-48%	+48%	-48%	+48%
End-of-life scenario	Various scenarios		-0.0%	+0.0%	-0.0%	+0.1%	-0.0%	+0.1%	-0.0%	+0.0%	-0.2%	+0.4%	-2.9%	+4.2%	-2.9%	+4.1%
Dryer electronics unit process	PWB	—	—	—	—	—	-6.0%	—	-2.7%	—	—	—	—	—	—	—
Cotton roll towel reuses	-32%	+26%	—	—	—	—	—	—	—	—	+11%	-4.9%	—	—	—	—
Paper towel pulping process	-25%	71%	—	—	—	—	—	—	—	—	—	—	-3.5%	+9.8%	—	—
Paper towel mass	-49%	+102%	—	—	—	—	—	—	—	—	—	—	-45%	+93%	—	—
Allocation of recycled content	WT[c]	ISO	—	—	—	—	—	—	—	—	—	—	—	—	-4.6%	+6.8%
Manufacturing location	US	—[d]	-1.3%	—	-1.3%	—	-0.7%	—	-0.3%	—	-5.2%	—	-0.6%	—	-0.6%	—
Use location	FR	—[d]	-77%	—	-81%	—	-80%	—	-84%	—	-11%	—	-41%	—	-40%	—

(a) Change shown for impact of hypothetical all-hydropower or all-coal grids in kg CO_2 eq per kWh relative to baseline grid impact.

(b) Change shown for impact of unbleached sulfate pulp (low) or chemi-thermomechanical pulp (high) in kg CO_2 eq per kg pulp relative to baseline pulping process impact.

(c) Waste treatment and allocation based on ISO 14049 [61] (see Section A.4).

(d) Baseline represents maximum impact.

Impact sensitivity to uncertainty is summarized in Table 47 for both the scenario uncertainty analysis and the bill of activities uncertainty analysis. Minimum and maximum values resulting from each Monte Carlo simulation for a drying system (see Tables 14 and 17) are shown as absolute results as well as relative to the system's baseline impact. The range in relative GWP for each drying system indicates that uncertainty can lead to wide variation in system impact. It is very unlikely, however, that drying system impact will be as high or as low as the results in Table 47 suggest because these minimum and maximum values represent extreme scenarios (e.g. very short use of a high lifetime usage hand dryer on a hydropower-fueled electric grid or very long use of a low lifetime usage dryer on a coal-fueled electric grid).

The results in Table 47 also indicate that the drying system GWP ranges overlap (e.g. the range of feasible values of the cotton roll towel system fall entirely within the range of feasible values of the paper towel system), which can potentially lead the systems to switch rank order depending on the analysis assumptions. The probability of the systems switching rank order, however, will depend on the systems' GWP probability distributions (shown in Figures 33 and 35). Additional analyses in Section 5.2 were conducted to assess the likelihood that drying system GWP is less than that of the aluminum Dyson Airblade™ hand dryer system and to ascertain that the difference in the GWP distributions and their means were statistically significant.

Table 47 Summary of minimum and maximum GWPs of drying system from uncertainty analyses.

	Airblade™, aluminum	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels, virgin
Baseline	4.59	8.14	17.8	10.9	15.5
Scenario uncertainty analysis (drying-driven dry times)					
Minimum, absolute	0.36	0.55	0.63	8.11	4.78
Maximum, absolute	8.83	15.8	34.9	25.5	28.4
Minimum, relative to baseline	-92%	-93%	-96%	-26%	-69%
Maximum, relative to baseline	+92%	+94%	+96%	+134%	+83%
Bill of activities source uncertainty analysis (baseline scenario, measured dry times)					
Minimum, Absolute	2.14	3.07	6.60	7.54	10.6
Maximum, absolute	17.8	20.9	65.4	16.6	21.9
Minimum, relative to baseline	-53%	-62%	-63%	-31%	-32%
Maximum, relative to baseline	288%	157%	267%	52%	41%

A.8.3 Consistency check

The consistency check assesses whether assumptions, methods, and data for each product system are consistent with each other as well as with analysis goal and scope. This information is summarized in Table 48. The right-most column, labeled “Consistency across systems,” indicates whether data is consistent among the product systems, whereas check marks (✓) in the boxes symbolize whether the data is consistent with the goal and scope of the analysis. *Data source* lists where the bill of activities and the unit process inventory data were obtained. The accuracy of these data is reflected in the *data accuracy* row. *Data age* represents when the data was collected and is only included for the bill of activities data. (It should be noted, however, that results were calculated using the most recent version of ecoinvent available.) By contrast, *time-related coverage* represents the age of the technology itself—whether it was recently developed or is a mix of old and new. *Technology coverage* indicates which of the old and/or new technologies are considered and *geographical coverage* refers to the geographic area from which the data was collected (e.g. US is used for the Dyson Airblade™ hand dryer’s bill of activities because it represents the hand dryer for the US market, whereas the inventory data is based on unit processes using data from US or Europe).

Table 48 Data consistency check.

	Airblade™, aluminum	Airblade™, plastic	XLERATOR®	Standard dryer	Cotton roll towels	Paper towels	Consistency across systems
Bill of activities data source	✓ Manufacturer	✓ Manufacturer	✓ Prior LCA study	✓ Prior LCA study	✓ Prior LCA study	✓ Prior LCA study	Very good
Unit process inventory data source	✓ ecoinvent v2.1	✓ ecoinvent v2.1	✓ ecoinvent v2.1	✓ ecoinvent v2.1	✓ ecoinvent v2.1 ETSA report [12]	✓ ecoinvent v2.1	Very good
Data accuracy	✓ Very good	✓ Very good	✓ Good	✓ Good	✓ Good	✓ Good, except for recycled pulp production	Good
Data age (bill of activities)	✓ Within 1 year	✓ Within 1 year	✓ Within 2 years	✓ Within 2 years	✓ Within 5 years	✓ Within 2 years	Very good
Technology coverage	✓ Specific to product, except for mfg location and transport. assumptions	✓ Specific to product, except for mfg location and transport. assumptions	✓ Specific to product, except for mfg location and transport. assumptions	✓ Representative of product category	✓ Representative of product category	✓ Representative of product category	Good
Time-related coverage	✓ Representative of current situation	✓ Representative of current situation	✓ Representative of current situation	✓ Representative of current situation	✓ Representative of current situation	✓ Representative of current situation	Very good
Geographical coverage (bill of activities)	✓ US	✓ US	✓ US	✓ US	✓ Europe	✓ US	Good
Geographical coverage (unit process inventory data)	✓ US or region with similar technology (e.g. Europe)	✓ US or region with similar technology (e.g. Europe)	✓ US or region with similar technology (e.g. Europe)	✓ US or region with similar technology (e.g. Europe)	✓ US or region with similar technology (e.g. Europe)	✓ US or region with similar technology (e.g. Europe)	Very good

✓ symbolizes consistency with goal and scope of study.