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UNCERTAINTIES IN LCA

Analyzing uncertainty in a comparative life cycle assessment of hand drying systems

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Abstract

Purpose: The goal of this study is to evaluate and compare the environmental impact (with a focus on global warming potential) of five hand-drying systems: hands-under (HU) dryers, high-speed hands-under (HSHU) dryers, high-speed hands-in (HSHI) dryers, cotton roll towels, and paper towels. Another objective is to incorporate uncertainty into this comparative LCA as a means of understanding the statistical robustness of the difference between the environmental impacts of the hand drying systems.

Methods: We conducted a life cycle assessment in accordance with the ISO 14040/14044 standards using data primarily from publicly available reports. As part of the study we performed a parameter uncertainty analysis for multiple scenarios to evaluate the impact of uncertainty in input data on the relative performance of products. In addition, we conducted a probabilistic scenario analysis of key drying system parameters in order to understand the implications of changing assumptions on the outcomes of the analyses.

Results and discussion: The scope of the analyses enabled us to draw robust conclusions about the relative environmental performance of the products. We can say with a high degree of confidence that the high speed dryers have a lower impact than paper towels and cotton roll towels. Differentiating the performance of the hand dryers requires being more specific about framing assumptions. Under certain conditions, the HSHI dryer is expected to have a lower impact than the HU and HSHU dryers. However, under other conditions, one cannot say that the HSHI dryer is clearly better than the other dryers. We cannot differentiate the performance between the HU dryer, cotton roll towels, and paper towels.

Conclusions: This work demonstrates the importance of going beyond traditional uncertainty analyses for comparative LCAs that are used for assertions of relative product environmental impact. Indeed, we found instances where the conclusions changed as a result of using the probabilistic scenario analysis. We outline important elements that should be included in future guidance on uncertainty analyses in comparative LCAs, including conducting parameter and scenario uncertainty analyses together and then using the outcomes to guide selection of parameters and/or choices to analyze further.

Keywords Life cycle assessment • Hand drying systems • Parameter uncertainty • Scenario analysis

1 Introduction

Characterizing the relative environmental impact of everyday life activities (and the products that enable them) has been a staple of life cycle assessment since the inception of the field. The relative environmental impact of hand drying systems is a clear example of this. Interest by the public at large is made plain by broad coverage of this topic in the media (Koerner 2008; Clarren 2007; Skoczen 2009; Adams 2007; Watson 2007). Interest within the technical and academic community is clearly evidenced by no less than 9 studies that target this very topic, including a streamlined life cycle assessment (LCA) conducted for Airdri Ltd. and Bobrick Washroom Equipment that compares a standard warm air dryer to paper towels (Environmental Resources Management 2001), a hand dryer-towel comparison produced by myclimate and commissioned by Dyson in Switzerland (Wettstein 2009), a comparison between cotton roll towels and paper towels commissioned by Vendor (Schryver and Vieira 2008), and some calculations made by the Climate Conservancy for Salon (Clarren 2007). More comprehensive life cycle assessments that comply with the ISO 14040 and 14044 life cycle assessment standards (International Organisation for Standardisation 2006) are also available. These include a study for the European Textile Services Association (ETSA) that compares cotton roll towels to paper towels (Eberle and Möller 2006), another investigating multiple types of tissue products for Kimberly-Clark (Madsen 2007), and a third for Excel Dryer that compares its XLERATOR® hand dryer to a standard warm air dryer and paper towels (Dettling 2009). Dyson has also conducted a life cycle assessment of its Dyson Airblade™ hand dryer in accordance with the PAS 2050 standard (British Standards Institute 2008) in order to obtain a Carbon Reduction Label from the Carbon Trust (Dyson 2010).

Among all these studies, the one by myclimate (Wettstein 2009) is the most comprehensive in the scope of hand drying systems considered — a high-speed hands-in dryer (the Dyson Airblade™ hand dryer), a standard warm air dryer, cotton roll towels, and paper towels. It does not include the hands-under variant of high-speed dryers, however. By contrast, the report conducted for Excel Dryer includes a high-speed hands-under dryer (the XLERATOR® hand dryer) but does not consider a high-speed hands-in dryer or cotton roll towels. Because of the studies' differing functional units, assumptions, and data, life cycle assessment outcomes cannot be easily compared. We conducted this study in order to address this gap. Thus, the primary goal of the study 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.

A second and equally important objective is to incorporate uncertainty into this comparative LCA as a means of understanding the statistical robustness of the difference between hand drying system environmental impacts. Lloyd and Ries

(2007) provide definitions for the types of uncertainty in their analysis of the LCA uncertainty literature. Parameter uncertainty is derived from uncertainty in observed or measured values. In an LCA context, it generally refers to uncertainty in the input data used to create life cycle inventories (LCI). Scenario uncertainty is related to the choices made in framing the LCA and constructing scenarios. This may be driven by inherent variability in geographic locations or situations in the analysis, or it may be due to methodological decisions around issues such as scope and allocation for which there is no clear direction. Lloyd and Ries also discuss model uncertainty, which relates to the structure and mathematical relationships in models. In addition, there is uncertainty in the impact factors used to translate the life cycle inventory to life cycle impact.

Relatively few studies have been reported in the literature that explore the role of uncertainty in comparative life cycle assessments (Hong et al. 2010; Huijbregts 1998; Huijbregts et al. 2003; de Koning et al. 2010). Of these, all have evaluated the impact of parameter uncertainty. As a representative example, Huijbregts (1998) quantified the implication of uncertainty in the mass of the functional unit, the rate of recycling, and many of the associated inventory items on the ability to resolve the environmental performance of two alternative roof gutter systems. Methods typically involve defining a baseline set of conditions (or scenarios) around which a Monte Carlo simulation or other analysis is conducted; ratios or differences of impacts between products being compared are then calculated from analytical results. Indeed, current international product carbon footprint standards suggest this type of analysis (World Resources Institute and World Business Council for Sustainable Development 2011). While these approaches are important for the consideration of parameter uncertainty, they only provide insight for a given scenario. Huijbregts first pointed out this limitation and demonstrated an approach to address it by examining four specific scenarios (two end-of-life allocation rules and two future GWP reference scenarios). Later Huijbregts et al. (2003) demonstrate a more expansive comparative assessment that includes both parameter and scenario uncertainty. Specifically, in comparing two insulation alternatives for a Dutch home, Huijbregts et al. evaluated aggregate parameter, scenario, and model uncertainty across thirty-two specific scenario and model conditions. Finally, de Koning et al. explored scenario uncertainty due to analyst choices, but only insofar as uncertainty due to the choices of other analysts are embedded in available databases and secondary data. Instead, the focus of de Koning is on demonstrating the importance of the decision framing scenario (e.g., evaluating alternatives within the firm or comparing products across firms) on the ability to resolve alternatives.

There is limited attention paid in LCA standards on how to comment on the significance of the difference between products' environmental impacts. The ISO 14044 standard recommends that "An analysis of results for sensitivity and uncertainty shall be conducted for studies intended to be used in comparative assertions intended to be disclosed to the public." (International Organisation for Standardisation 2006) While this statement is important, there is no further guidance in the ISO 14044 standard on how to conduct sensitivity and/or uncertainty analyses to support comparative assertions. The ILCD Handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010), the PAS 2050 (British Standards Institute 2008), and the recently released Product Life Cycle Accounting and Reporting Standard from the GHG Protocol (World Resources Institute and World Business Council for Sustainable Development 2011) each have sections discussing uncertainty. Although these documents contain definitions of uncertainty similar to those provided by Lloyd and Ries (2007), the guidance is limited in that the focus is on qualitative characterizations of data quality and quantitative calculations of uncertainty in input data (i.e., parameter uncertainty) with minimal discussion about how to conduct a full uncertainty analysis. For instance, The ILCD Handbook discusses the importance of sensitivity analysis (like the ISO 14044 standard) and states that scenario analysis and uncertainty calculations are the methods to support the sensitivity analysis. However, there is limited guidance in the handbook on the differences between sensitivity analysis, scenario analysis, and uncertainty analysis. This is almost certainly part of the motivation for calls from the literature for more guidance on uncertainty analyses in standards (Draucker et al. 2011).

We will not completely address this gap of meaningful guidance on uncertainty analyses for comparative LCAs in this paper. However, we believe that the analyses conducted as part of this case study on hand dryers can illuminate the importance of elements that should be included in such guidance and will add to the body of knowledge in this area. We conduct parameter uncertainty analyses for several scenarios following the approach proposed by Huijbregts and implied in the standards. In addition, we go beyond these traditional analyses by conducting further probabilistic scenario analyses of key parameters in order to understand the implications of changing key assumptions about the characterization of uncertainty in the parameters and correlation of parameters among compared alternatives on the outcomes of the analyses. We use these analyses to make recommendations for important elements that should be included in future guidance on uncertainty analyses in comparative LCAs.

2 Methods

2.1 Goal and scope

The goal of this study is to compare the environmental impacts of a broad range of hand drying systems using a consistent basis and to analyze uncertainty in order to comment on the statistical significance of the differences between the systems. The study was conducted in accordance with the ISO 14040 and 14044 standards (International Organisation for Standardisation 2006), including critical review. A report that includes the full details of the study and the critical review comments is available (Montalbo et al. 2011), but we have included information on key data and methodological assumptions here and have summarized other important details in the Electronic Supplementary Material available online. This paper builds on the original report by providing a more comprehensive uncertainty analysis, presenting a more precise evaluation of the ability to resolve alternatives, and using this case study as a platform to discuss the issues associated with comparative life cycle assessment.

The scope of the study includes five hand-drying systems, detailed in Table 1, which describes the method used by each product to dry hands, and references the primary source of product material and performance data (the actual data are in the Electronic Supplementary Material). In addition to the dryers and towels themselves, 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 system.

Drying a single pair of hands represents the functional unit. Since the electric hand dryers (HU, HSHU, and HSHI) dry numerous pairs of hands over their lifetimes, their environmental impacts are 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 (see Section 1 in the Electronic Supplementary Material for details on allocations per functional unit).

The system boundaries encompass all life cycle phases, from cradle to grave, along with transportation between and within each phase. Details on the system boundary and the life cycle stages are included in Section 1 of the Electronic Supplementary Material. All systems, with the exception of paper towels, are assumed to be manufactured in China. Upstream processes such as the mining of ore or the extraction and refining of petroleum for vehicle fuel are included within system boundaries. Only the energy required to manufacture dryers or towels is accounted for in the calculation of manufacturing phase impact—production of capital equipment is considered outside the scope for this phase due to limitations on data availability (it is included in upstream processes that are part of the ecoinvent database).

The use phase takes place in the United States. For the electric hand dryers, use phase impact is solely due to the production and distribution of electricity required for operation. The use phase for 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. 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 Life cycle inventory and impact assessment

We obtained data used to generate drying system life cycle inventories from a variety of existing sources outlined in Section 2 in the Electronic Supplementary Material (the primary sources are summarized in Table 1). Baseline assumptions used to generate hand-drying system life cycle inventories are listed in Table 2. The Electronic Supplementary Material provides details on the sources for the data, but the hand drying time data are particularly noteworthy. Hand drying time is characterized in two ways and will be analyzed in the uncertainty analyses. The first is drying-driven usage, where a user dries his hands to either to a defined dryness standard—in this case NSF Protocol P335 (NSF 2007) (the baseline dry times are based on tests run using this standard)—or to a user's personal dryness comfort level. This assumes users are using the products as recommended. The second is time-driven usage, where users employ the dryer for a prescribed amount of time, regardless of the dryness of the hands. This assumes users are not as concerned about having completely dry hands. The times in Table 2 are based on measurements conducted in accordance with the NSF protocol (representing drying-driven usage), but the uncertainty analyses will also present results using drying times reported by hand dryer manufacturers and time-driven usage scenarios (and are listed in Section 2.1.3 of the Electronic Supplementary Material). The only significant difference between the measured and reported dry times is that the HSHU reported dry time is 12 seconds as compared to the 20 second measured dry time.

The importance of the hand drying time characterization has led us to use three scenarios in the uncertainty analyses: 1) baseline scenario assumptions including hand dryer measured dry times based on the NSF Protocol P335; 2) the same baseline scenario assumptions except for dryer dry times based on reported times from manufacturers (detailed in Section 2.1.3 in the Electronic Supplementary Material); and 3) the same baseline scenario assumptions and reported dry times and a consistent printed wiring board (PWB) unit process data used for all three hand dryers. The original data sources for the three dryers had used different sets of unit process data: the generic unit process, "Electronic component, active, unspecified," was used to represent the control and optics assemblies in original studies on the HSHU and the HU dryers, whereas a more specific unit process, "Printed wiring board, through-hole, lead-free surface," was specified for the HSHI dryer's inventory; the latter process has a lower impact. The PWB has a significant impact on the production impact of the dryers and thus, the choice of the PWB can be important. We chose to defer to the judgment of the original LCA analysts in their selection of inventory data for the PWB and have used those in our baseline analyses and scenario 2. However, we believe it is unlikely the PWBs in the three dryers would be significantly different, which is why we have analyzed the impact of changing this assumption in scenario 3.

We obtained background inventory data for intermediate flows from the ecoinvent v2.1 database (Frischknecht et al. 2007). The majority of the data were used directly from the database, but in a few cases we needed to make some modifications to ecoinvent datasets because of a lack of existing inventory data. These cases and the associated data are listed in Section 2.2 of the Electronic Supplementary Material.

We conducted all life cycle analyses using a combination of models in SimaPro LCA software and Microsoft Excel with a Crystal Ball extension. The specific instances for each software tool are described in the uncertainty analysis methodology section below.

In the full report we used IMPACT 2002+ (Hischier et al. 2010) to calculate life cycle impact. However, due to resource limitations uncertainty analyses were only conducted using the global warming potential (GWP) life cycle impact assessment (LCIA) methodology (Hischier et al. 2010), which incorporates the impact of gaseous emissions according to their potential to contribute to global warming based on the 100 year characterization factors published in 2007 by the Intergovernmental Panel on Climate Change (IPCC) (2007). Thus, only results using GWP are presented here and the conclusions should not be generalized to other impact measures without further analysis.

2.3 Uncertainty analysis methodology

We conducted two types of analyses to study the impact of uncertainty on the outcomes of our comparative LCA: a parameter uncertainty analysis and a probabilistic scenario analysis. The former is consistent with the approach implied in the standards, but the latter has not been explicitly outlined in the literature or standards. A scenario analysis is presumably a study of the impact that various scenarios have on the outcomes of the LCA (it is not explicitly defined in the standards). This is typically done using analyst-defined, discrete scenarios (where a scenario is simply a defined set of parameters and framing assumptions). We have extended this by defining ranges for specific types of parameters that are particularly important when defining scenarios and used probabilistic techniques to explore thousands of potential scenarios.

This type of scenario analysis is not to be confused with a scenario uncertainty analysis. Various sources in the literature described in the introduction have defined scenario uncertainty as being about choices made in framing the LCA (typical examples include allocation methods or boundary decisions) and hence, are not typically analyzed in a parameter uncertainty analysis. Our scenario analysis includes some of these issues, but it also includes analysis of parameters that would be studied in a sensitivity or scenario analysis because of their high impact or high profile.

We did not characterize uncertainty in the models or in the impact factors due to a lack of information on how the uncertainty should be defined. Because these are not included in our analysis, the method underestimates actual uncertainty and therefore overestimates the ability to resolve differences between alternatives. Future work should investigate the significance of this limitation.

2.3.1 Parameter uncertainty snalysis

In our uncertainty analyses, parameter uncertainty was characterized using the pedigree matrix approach implemented in the ecoinvent database (Frischknecht et al. 2007) because it represents the most widely used methodology in LCA for characterizing uncertainty. Details on the approach and the specific scores used in this analysis are provided in Section 3 of the Electronic Supplementary Material. A lognormal distribution was used for all input data because it always remains positive and is consistent with the data available in the ecoinvent database and the pedigree matrix approach.

We conducted parameter uncertainty analyses using pair-wise Monte Carlo simulations in SimaPro. The difference in these results was evaluated using a one-way analysis of variance on the means and through a pairwise comparison indicator. The latter involved analyzing a pair of products simultaneously and calculating the ratio of impacts for the two products in each simulation (the ratio is known as the comparison indicator (CI) as proposed by Huijbregts (1998)). The pair-wise analysis ensures a correlated analysis. That is, values selected in each simulation for parameters that are common within and among the analyzed pair will be the same. (There may be instances where this correlation constraint is unrealistic (e.g., it may be reasonable to expect that materials common to the two products in the analysis come from different sources) and thus, the correlation may create an appearance of more overlap in environmental impact than actually exists.) A result of the analysis is a cumulative frequency distribution of comparison indicators ($F(CI)$) from all simulations. From $F(CI)$, we can derive the fraction of simulations in which the modeled impact of one product exceeded the other. Because the current analysis excludes some forms of uncertainty (i.e., model and impact factor), we have chosen to identify difference in the two products at two conservative threshold values of 90% and 95%. . That is a comparison indicator of greater than or equal to one is observed in more than 90% or 95% of the trials.

We conducted pair-wise analyses of all product combinations (ten total combinations) for a given set of conditions (or scenario) using 1,000 simulations in each comparison. These comparisons were conducted for three different scenarios (described in the previous subsection) for a total of thirty analyses.

2.3.2 Probabilistic scenario analysis

A typical uncertainty analysis for a comparative LCA will include a stochastic analysis of parameter uncertainty for a selected number of discrete scenarios, which is consistent with the parameter uncertainty analysis we have described here. While this is important, the analysis represents a small sample of the overall scenario space. That is, there will likely be countless scenarios that can be derived from various combinations of methodological choices and values for parameters that are evaluated in scenarios. For this paper, we have attempted to explore the scenario space more broadly by using Monte Carlo analysis to randomly sample values for a set of drying system parameters, such as use intensity or electric grid mix, and repeat this process thousands of times to create a wide range of scenarios. This enables us to comment on the robustness of a claim that one product has a lower environmental impact than another by stating how often a product is observed to have a lower modeled impact across a wide range of scenarios.

Our probabilistic scenario analysis was implemented using Microsoft Excel with Crystal Ball for the Monte Carlo method and the same inventory and unit process data used in the parameter uncertainty assessment in SimaPro. Unlike the parameter uncertainty analyses, all five products can be analyzed simultaneously for this spreadsheet model. The parameters varied in the analysis are shown in Table 3 along with their baseline values, ranges, and distributions; all other parameter values remained the same as in the baseline scenario. All of the parameters (with the exception of the composting assumption which is binary) have a uniform distribution because we are assuming that all parameter values and scenarios are equally likely (in the absence of alternative information). The use of a statistical distribution on the parameter values and the Monte Carlo analysis enable us to generate numerous combinations of scenarios across the scenario space.

The set of parameters shown in Table 3 was selected because they are parameters for which the selection of a representative value was difficult or infeasible due to a lack of solid data or because they represented variation in geographical scope (i.e., use grid mix and municipal solid waste incineration fraction). In addition, a number of the parameters have a strong influence on drying system environmental performance, as dictated by sensitivity analyses detailed in the full report. Details on the motivation for the specific ranges for each parameter are provided in Section 4 of the Electronic Supplementary Material, along with details about correlation assumptions for the parameters. Correlation assumptions in a scenario analysis are not straightforward, but can be critical (see (de Koning et al. 2010)). Due to this importance, we conducted multiple analyses in which hand dryer use intensity is either correlated or uncorrelated. We also changed the usage pattern to be either drying-driven or time-driven and whether the PWB unit process is consistent or inconsistent in each scenario uncertainty analysis.

While we have attempted to select sensitivity analysis ranges which covered the majority of reasonable and significant cases, it is possible that some cases are excluded. As such, the conclusions drawn here should not be generalized to other cases without further study.

We conducted six sets of scenario uncertainty analyses with multiple combinations of these three framing assumptions (dryer use intensity correlation, usage pattern, and PWB unit process consistency). Each scenario uncertainty analysis involved 20,000 Monte Carlo simulations. The differences in the means of the resulting simulations were tested using the Steel-Dwass variant of the Kruskal-Wallis test which examines significance of difference in sample means while controlling for alpha across the entire set of comparisons (details are provided in Section 5 of the Electronic Supplementary Material). Differences in the sample medians were evaluated by a sign test on each combination of samples. Additionally, in each simulation we calculated a comparison indicator for the relative impact of two products in the same manner as the parameter uncertainty analysis. We used the same 90% and 95% frequency levels as thresholds for evaluating whether one product has a lower environmental performance than another across the scenario space.

3 Results

3.1 Deterministic

The deterministic GWP results associated with drying a single pair of hands for the three scenarios described in Section 0 are shown in Fig. 4. The figures illustrate that there are differences in overall expected impact among the drying systems, but in some cases this can depend on the scenario under consideration. They also shows that the use phase is expected to be the driving factor for the GWP of electric hand dryers (due to the electricity consumption during use) and the cotton roll towels (from washing the towels), whereas manufacturing is expected to be the driving factor for the paper towel GWP. If reported dry times are used (scenario 2, results in Fig. 4b), the HU dryer impact decreases 3% (relative to the baseline results with measured dry times in Fig. 4a) to 17.3 g CO_2 eq (due to a dry time decrease from thirty-one down to thirty seconds) and the HSHU dryer decreases 34% to 5.4 g CO_2 eq (due to a dry time decrease from twenty down to twelve seconds); the other three dryer system impacts remain unchanged. If reported dry times and a consistent PWB unit process are used (scenario 3, results in Fig. 4c), the HU dryer impact decreases 6% (relative to the baseline results with measured dry times in Fig. 4a) to 16.8 g CO_2 eq and the HSHU dryer decreases 40% to 4.9 g CO_2 eq; once again the other three dryer system impacts remain unchanged. Although it may appear that there are clear differences among the products, with this analysis alone one cannot comment on the robustness of comparisons between the products, particularly when making comparisons across the three scenarios.

Contribution analyses have highlighted the key drivers of environmental impact for the hand drying systems for global warming potential (Montalbo et al. 2011). For hand dryers, environmental impact is driven by the use phase energy consumed in the active use of the hand dryer. Within the production phase (including materials and manufacturing), key contributors are the housing materials, electricity used in production, and the printed wiring boards for the controls and optics assembly.

For cotton roll towels, 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. 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. 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.

For paper towels, 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). 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.

3.2 Parameter uncertainty

The outcomes of the parameter uncertainty analyses are shown in Table 4. (Outcomes from the one-way analysis of variance test, in particular, and the resulting significance of differences in sample means are reported in Table 28 of Section 5 of the Electronic Supplementary Material). These outcomes are consistent with, but generally less stringent than the comparison indicators results discussed here.) Results from pair-wise comparisons are listed for three different scenarios in Table 4. In some instances, one drying system is better than another in all simulations and across all three scenarios. For example, the high-speed hands-in dryer outperformed the hands-under dryer in every simulation in all three scenarios. In fact, both high-speed dryers are almost always better than the other three products (the one exception being the HSHU and cotton roll towels whose similarity cannot be rejected at 90% (or 95%) confidence when the dryer is evaluated at the measured dry time). When accounting for uncertainty in input data, we can clearly say with confidence that the high-speed dryers have a lower GWP than the other drying systems *for these three scenarios*. However, the results are much less clear when comparing the two high-speed dryers (in only one scenario can the similarity of the two products be rejected at 90% or 95% confidence), or when comparing cotton roll or paper towels and the hands-under dryer.

3.3 Probabilistic scenario analysis

The resulting GWP frequency distributions for the 20,000 iterations of the scenario uncertainty analysis are presented in Fig. 5 for both drying-driven (see Fig. 5a) and time-driven (see Fig. 5b) usage patterns. 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 HSHU and HU dryer systems have a much wider spread than that of the HSHI dryer system when drying-driven usage is considered due to the broader range of dry times for the first two systems. Statistical tests on the significance of difference for the central tendency of these results (Kurskal-Wallis test on means and sign test of medians) are presented in Tables 29 and 30 in Section 5 of the Electronic Supplementary Material. These results are consistent with, but generally less stringent (i.e., identify more statistically significant differences) than the comparison indicators results discussed here.

While the frequency distributions of drying system GWP in Fig. 5 clearly overlap, it is important to look at the comparison indicator results in order to understand the impact of correlation. Comparison indicator distributions for the GWP of different drying systems relative to that of the HSHI dryer are shown in Fig. 6 given both drying-driven and time-driven usage patterns. The HSHI dryer was chosen as the point of comparison because it has the lowest impact in the baseline deterministic analyses. 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. Overall, however, the GWP of the high-speed hands-in dryer is still lower than that of any given drying system in over 92% of the iterations.

The results in Fig. 5 and Fig. 6 assume correlated use phase grid mix and use intensity for the hand dryers. The HSHI dryer system almost always has the lower impact for a given scenario due to this key assumption of correlated usage (i.e., when the high-speed hands-in dryer is used at low intensity, the other dryers are as well, leading the high-speed hands-in dryer 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 other drying methods have a lower impact. In scenarios where the HSHU dryer has a high lifetime usage, the HSHI dryer a low lifetime usage, and the use phase takes a low-carbon grid mix, the HSHU system has the lower impact. In another scenario, the longer HSHI hand dryer dry times associated with time-based usage increase the frequency at which the other drying systems will have a lower impact than the HSHI dryer system.

Results from a range of different correlation, use intensity, and unit process framing assumptions are presented in Table 5 using the comparison indicator metric as the basis for evaluating the frequency at which one product's GWP is lower than that of another. It is particularly important to explore alternative correlation assumptions because the three hand dryers are inherently different and may elicit different user behavior. The six sets of framing assumptions are essentially meta-scenarios for each set of simulations that explore 20,000 specific scenarios. (The results in Fig. 5a and Fig. 6a were generated using the meta-scenario 1, whereas the results in Fig. 5b and Fig. 6b were generated using the meta-scenario 4. Additionally, they only represent drying system impact relative to the HSHI dryer—corresponding to the top four rows in Table 5.)

The results involving the HSHI dryer as a comparator indicate that removing the correlation between dryer use intensities increases the frequency at which the GWPs of the HSHU and HU dryer systems are less than that of the HSHI dryer system, particularly for time-driven usage. The comparison indicators for cotton roll towel and paper towel systems with the HSHI dryer are unaffected by usage correlation. Reconciling the PWB unit process for the HSHU and the HU dryers also increases the number of Monte Carlo-generated scenarios that result in their GWPs undercutting the HSHI dryer GWP; in fact, these lead to comparison indicator frequencies below the 90% threshold. Time driven usage patterns (which are longer for the HSHI product) also decreases the differentiation between the HSHI product and all other alternatives. In fact, under time-driven assumptions, the HSHI and HSHU cannot be declared different for a more stringent 95% threshold (and is only declared different for one framing assumption (4) for the less stringent 90% threshold). For the HSHU system, use of the same PWB unit process and time-driven usage assumptions impacts the GWP of the alternatives enough so that in half the Monte Carlo-generated scenarios, its impact is less than that of the HSHI dryer system. In fact, this comparison is the only example where significance testing cannot reject the null hypothesis that the median impacts of these two products are the same (see Section 5 of the Electronic Supplementary Material). This result is notably different than the results from the first set of framing assumptions where the HSHI dryer impact is almost always lower than the HSHU dryer impact.

The comparison of the HSHU dryer with other drying systems is consistent with HSHI dryer results: the HSHU dryer exceeds the 90% threshold (i.e., can be declared significantly different) for all sets of framing assumptions for the cotton roll towels and paper towels (although it fails a more stringent 95% threshold for paper towels). However, it falls below the threshold (i.e., cannot be declared different) when compared to the HU dryer in uncorrelated time-driven use intensity meta-scenarios (numbers 5 and 6 in Table 5). The cotton roll towels, HU dryer, and paper towels all show significant overlap in impacts across all sets of framing assumptions. We cannot say with confidence that any one of them has a lower impact than another based on this scenario uncertainty analysis.

4 Discussion

After reviewing the outcomes of the parameter uncertainty analysis and probabilistic scenario analysis, it is valuable to assess how much confidence we have in asserting the difference between product environmental impacts (i.e., the statistical robustness of the comparison). The deterministic results in Fig. 4, although temptingly different for the five products, are clearly insufficient to draw meaningful conclusions because they represent a single scenario and do not take into account uncertainty in the input data. The outcomes of the parameter uncertainty analysis listed in Table 4 indicate that for the three scenarios considered we have statistical confidence that the high-speed dryers have lower GWPs than the other drying systems (the slight exception being HSHU dryer compared to cotton roll towels for measured dry times), but that the results are inconclusive when comparing the two high-speed dryers or when comparing paper towels and the hands-under dryer. When we combine this with the results of the probabilistic scenario analysis in Table 5, the conclusion that the high-speed dryer impacts are lower than the impacts of cotton roll towels and paper towels is strengthened. However, in two of the six meta-scenarios with time-driven and uncorrelated use intensity we cannot say with confidence that any of the three hand dryer systems have significantly different impacts because all comparison indicator frequencies are below the 90% threshold value. Furthermore, we cannot say with confidence that the HU dryer, cotton roll towels, or paper towels impacts are distinguishable from each other based on the fact that all three products had comparison indicator frequencies below the 90% threshold across all six meta-scenarios in the scenario uncertainty analysis when compared with one another.

Based on this information we can say with a high degree of statistical confidence that the high-speed dryers have a lower impact than paper towels and cotton roll towels across a broad set of scenarios. Differentiating the performance of the hand dryers compared to one another requires being more specific about framing assumptions. For drying-driven use (when consumers use the products as recommended), the HSHI dryer has a lower impact than the HU dryer in nearly all cases and a lower impact than the HSHU in the majority of cases. However, for time-driven use (when consumers are not as concerned about having equivalently or completely dry hands), one cannot say that the HSHI dryer is clearly better than the other dryers. Additionally, we cannot confidently differentiate performance between the HU dryer, cotton roll towels, and paper towels across this scenario space.

This last statement is important to consider. This analysis does NOT mean that these products are equivalent in any given scenario. It only means that when there is considerable scenario ambiguity and, therefore, the scenario space is large, it is not possible to reach a single definitive conclusion. If the decision-maker is able to further refine the scenario space (e.g., credibly establish the use location or the drying habits of the user population), further resolution is plausible. The case of comparing cotton roll towels and paper towels is particularly illustrative of this point because the results of the parameter uncertainty analysis (see Table 4) indicated that cotton roll towels had a statistically significant lower impact than paper towels for three specific scenarios. However, the probabilistic scenario analysis indicated that there was significant overlap in impacts across all six meta-scenarios and one could not assert that one product clearly had a lower impact than the other across a broad scenario space. This motivates the importance of both going beyond a typical parameter uncertainty analysis with a few scenarios to a broader exploration of scenario uncertainty and to always revisit results with the ultimate decision-maker to ensure that further information cannot be brought to bear or that the decision space cannot be further divided.

This work demonstrates the importance of conducting uncertainty analyses for comparative LCAs that are used for assertions of relative product environmental impact, as recommended in the several standards. Indeed, there are several recommendations that are included in the standards and are supported by this case study. First, broad assertions of relative impact (e.g., “Product *X* has a lower environmental impact than product *Y*.”) should only be made if the claim can be supported by uncertainty analyses that demonstrate that the claim is robust across all of these analyses. Second, if the uncertainty analyses reveal significant overlap in the distribution of impacts associated with the alternatives then assertions of relative product impact need to be stated alongside a clear definition of key framing assumptions (i.e., those assumptions that change the relative impact of the products). Finally, given the uncertainty in calculated environmental impact values and the variation across equally plausible scenarios, we discourage the use of quantifying relative impact (e.g., "Product *X* has a *Z*% lower environmental impact than product *Y*.") unless it is accompanied by a specific confidence level (such as those listed in Table 4 and Table 5).

While these broad recommendations in the standards are useful, there is almost no specific guidance on conducting uncertainty analyses for comparative LCAs. This case study has illuminated several issues that should be included in such guidance. First, although it is useful to aggregate the uncertainty of multiple parameters in the parameter uncertainty analysis, it will almost always be meaningful to conduct further uncertainty analyses with specific parameters held constant as a means of gaining insight on the impact of key parameters on outcomes. This is analogous to conducting parameter uncertainty analyses using multiple scenarios (as was done here and in other work), but there should be analytical justification for the selection of parameters that should be analyzed further. An example of this can be seen in (Mattila et al. 2011). Second, the literature discusses a separation between parameter and scenario uncertainty, but in reality there is overlap between the two in the implementation of uncertainty analyses because many choices (related to scenario uncertainty) manifest themselves as changes in parameters. Thus, parameter and scenario uncertainty should be analyzed together in an aggregate manner where possible and then analytical methods should be used to determine which parameters and/or choices should be analyzed further. Of course, there are some choices that cannot be aggregated, such as the use of different life cycle impact assessment methods, and these will still need to be analyzed separately.

As with any LCA, our analysis has several limitations. One limitation centers on data collection. We received data on the HSHI dryer directly from a manufacturer (which meant higher data quality and lower uncertainty), whereas we relied heavily on data from previously published studies for other hand drying systems and in some cases we did not have strong sources for key pieces of information (such as observed use intensity of the hand dryer systems). These challenges are common in comparative LCAs and motivate the need for expanded uncertainty analyses such as the ones we have presented here. In-depth uncertainty analyses are the strongest way to understand the implications of data limitations and other important assumptions (that are part of all LCAs) on comparative assertions of environmental impact. Additionally, due to resource limitations, uncertainty analyses were only conducted for GWP impacts. The results presented here shouldn't be generalized to other impacts without further study. Finally, this paper focuses on uncertainty analysis among the various systems. A complete assessment of uncertainty should also include sensitivity analysis to isolate the main drivers of impact (and possibilities for improvement).

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Table 1 Overview of hand drying systems evaluated

Hand Drying System	**Drying Method**	**Primary Source of Product Material and Performance Data**
Hands-under (HU) dryer	User places hands under the dryer nozzle and warm air blows onto the hands to dry them.	Generic dryer in (Dettling 2009)
High-speed hands-under (HSHU) dryer	Same as HU, but air is blown at high speeds.	Excel XLERATOR® dryer in (Dettling 2009)
High-speed hands-in (HSHI) dryer	User places hands into dryer and air blows at high speeds onto hands to dry them.	Dyson Airblade™ dryer with aluminum cover (Blower 2011)
Cotton roll towels (CRT)	User pulls cotton towel from roll in dispenser and dries hands by rubbing on towel.	Generic cotton towel in (Eberle and Möller 2006)
Paper towels (PT)	User pulls paper towels from dispenser and dries hands by rubbing on towels.	Kimberly-Clark 100% virgin paper towel in (Madsen 2007)

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Table 2 Assumptions used to generate hand-drying system life cycle inventories for the baseline analysis

Drying system	**Hands-under dryer**	**High-speed hands-under dryer**	**High-speed hands-in dryer**	**Cotton roll towels**	**Paper towels**
Functional unit	1 pair of dry hands				
Lifetime usage	350,000 pairs of dry hands over 5 years (Blower 2011; Dyson)				
Mass (+ manufacturing scrap) per dryer or towel	6.4 kg (0.9 kg) (Dettling 2009)	9.4 kg (1.12 kg) (Dettling 2009)	14.8 kg (1.43 kg) (Blower 2011)	16.2 g (2.2 g) (Eberle and Möller 2006)	1.98 g (0.08 g) (Dettling 2009)
Manufacturing location	China	China	China	China	US
Manufacturing energy per dryer or towel	156 MJ electricity (Dettling 2009)	156 MJ electricity (Dettling 2009)	146 MJ electricity (Dettling 2009)	431 kJ electricity 507 kJ gas (Eberle and Möller 2006)	14.7 kJ electricity 24.4 kJ gas (Dettling 2009)
Use location	US				
Use intensity	31 sec @ 2,300 W + 1.5 sec @ 1,150 W + 406 sec @ 0.4 W	20 sec @ 1,500 W + 1.5 sec @ 750 W + 429 sec @ 1 W	12 sec @ 1,400 W + 0 sec @ 0 W + 439 sec @ 1 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 (Franklin Associates 2011; United States Environmental Protection Agency 2009)				
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	0.45 kg cardboard (Dettling 2009)	0.27 kg cardboard (Dettling 2009)	2.94 kg cardboard (Blower 2011)	0.08 g polyethylene (Eberle and Möller 2006)	0.18 g cardboard (Dettling 2009)

Table 3 Parameter ranges and distributions for scenario uncertainty analysis

Independent parameters	Drying systems	Baseline	Range	Distribution
Lifetime usage	High-speed hands-in	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Lifetime usage	High-speed hands-under	350,000	150k – 550k pairs of hands over 5 yrs	Uniform
Lifetime usage	Hands-under	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	High-speed hands-in	CN average	0.019 – 1.44 kg CO_2 eq / kWh	Uniform
Manufacturing grid mix	High-speed hands-under	CN average	0.019 – 1.44 kg CO_2 eq / kWh	Uniform
Manufacturing grid mix	Hands-under	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	High-speed hands-in High-speed hands-under Hands-under Cotton roll towels	US average	0.016 – 1.32 kg CO_2 eq / kWh	Uniform
Use intensity	High-speed hands-in High-speed hands-under Hands-under	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
Municipal solid waste incineration fraction	All	19%	0% – 100%	Uniform
Compost	Paper towels, Cotton roll towels	N	Y, N	Binary

Table 4 Results of parameter uncertainty analyses. Numbers in bold are below the 90% threshold and, therefore, do not meet the prescribed significance level to be declared different

Drying system A	**Drying system B**	**Frequency $GWP_A > GWP_B$ ($F(CI \geq 1)$)** 1: Baseline assumptions, measured dry times	 2: Baseline assumptions, reported dry times	 3: Consistent PWB unit process, reported dry times
High-speed hands-in dryer	High-speed hands-under dryer	0.0%	**15%**	**35%**
High-speed hands-in dryer	Hands-under dryer	0.0%	0.0%	0.0%
High-speed hands-in dryer	Cotton roll towels	0.2%	0.2%	0.2%
High-speed hands-in dryer	Paper towels	0.0%	0.0%	0.0%
High-speed hands-under dryer	Hands-under dryer	0.0%	0.0%	0.0%
High-speed hands-under dryer	Cotton roll towels	**13%**	0.0%	0.5%
High-speed hands-under dryer	Paper towels	1.0%	0.0%	0.0%
Cotton roll towels	Hands-under dryer	7.8%	**10%**	**12%**
Cotton roll towels	Paper towels	1.2%	1.2%	1.2%
Paper towels	Hands-under dryer	**35%**	**41%**	**46%**

Table 5 Scenario uncertainty analysis results for six sets of framing assumptions. In the descriptions of the six sets of framing assumptions, "drying-driven" and "time-driven" refer to the ranges of use intensity times for the hand dryers (see **Table 3**), "correlated use" and "uncorrelated use" refer to whether the dryer use intensities are correlated, and "different PWB" and "same PWB" refer to whether the unit process used for the printed wiring board in the hand dryers is the same for all products or different. Numbers in bold are below the 90% threshold and, therefore, do not meet the prescribed significance level to be declared different

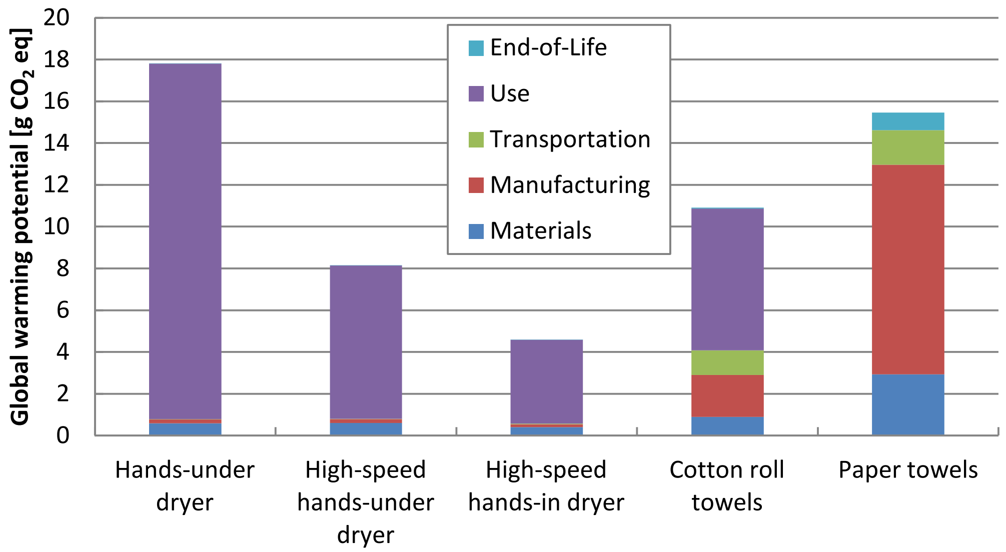
		Frequency $GWP_A > GWP_B$ ($F(CI \geq 1)$)					
Drying system A	**Drying system B**	1. Drying-driven, correlated use, different PWB	2. Drying-driven, uncorrelated use, different PWB	3. Drying-driven, uncorrelated use, same PWB	4. Time-driven, correlated use, different PWB	5. Time-driven, uncorrelated use, different PWB	6. Time-driven, uncorrelated use, same PWB
HSHI dryer	HSHU dryer	1.3%	4.5%	**14%**	7.3%	**37%**	**50%**
HSHI dryer	HU dryer	0.2%	0.2%	1.2%	1.0%	**19%**	**27%**
HSHI dryer	Cotton roll towels	0.0%	0.0%	0.0%	1.3%	1.3%	1.3%
HSHI dryer	Paper towels	0.4%	0.5%	0.4%	6.5%	6.2%	6.4%
HSHU dryer	HU dryer	1.0%	1.6%	0.5%	4.1%	**26%**	**26%**
HSHU dryer	Cotton roll towels	1.1%	1.2%	0.8%	2.7%	2.8%	1.9%
HSHU dryer	Paper towels	7.8%	7.6%	6.4%	9.4%	9.0%	7.8%
Cotton roll towels	HU dryer	**65%**	**65%**	**67%**	**85%**	**85%**	**87%**
Cotton roll towels	Paper towels	**59%**	**59%**	**60%**	**59%**	**59%**	**60%**
Paper towels	HU dryer	**57%**	**58%**	**59%**	**77%**	**78%**	**79%**

Fig. captions

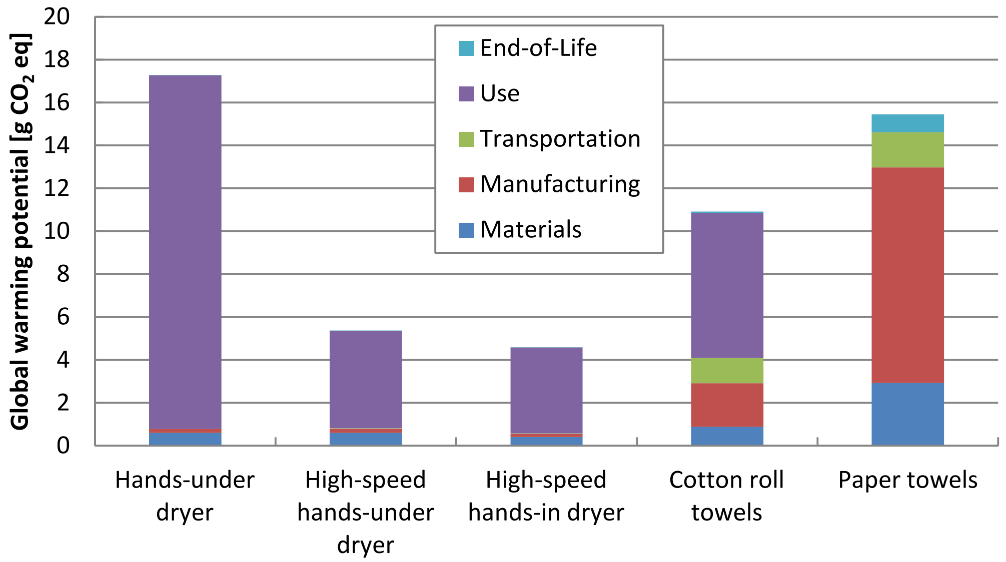
Fig. 1 Global warming potential for drying a single pair of hands under three scenarios: a) scenario 1: baseline assumptions, measured dry times; b) scenario 2: baseline assumptions, reported dry times; c) scenario 3: consistent PWB unit process, reported dry times

Fig. 2 GWP frequency distributions given (a) drying-driven and (b) time-driven usage patterns. Both plots are based on correlated use intensities and different printed wiring boards for the hand dryers (in accordance with meta-scenarios 1 and 4, respectively, from Table 5)

Fig. 3 GWP comparison indicator (CI) frequency distributions (calculated relative to high-speed hands-in dryer) given (a) drying-driven and (b) time-driven usage patterns. The dashed line indicates a comparison indicator value of one as a reference. Both plots are based on correlated use intensities and different printed wiring boards for the hand dryers (in accordance with meta-scenarios 1 and 4, respectively, from Table 5)



a) scenario 1: baseline assumptions, measured dry times



b) scenario 2: baseline assumptions, reported dry times

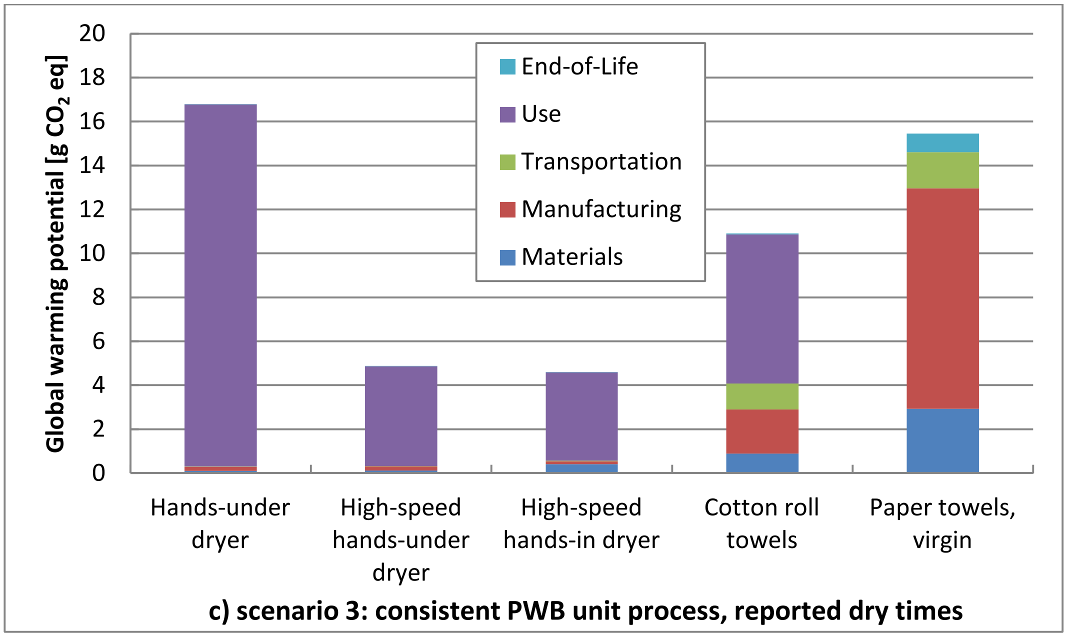


Fig. 4 Global warming potential for drying a single pair of hands under three scenarios: a) scenario 1: baseline assumptions, measured dry times; b) scenario 2: baseline assumptions, reported dry times; c) scenario 3: consistent PWB unit process, reported dry times

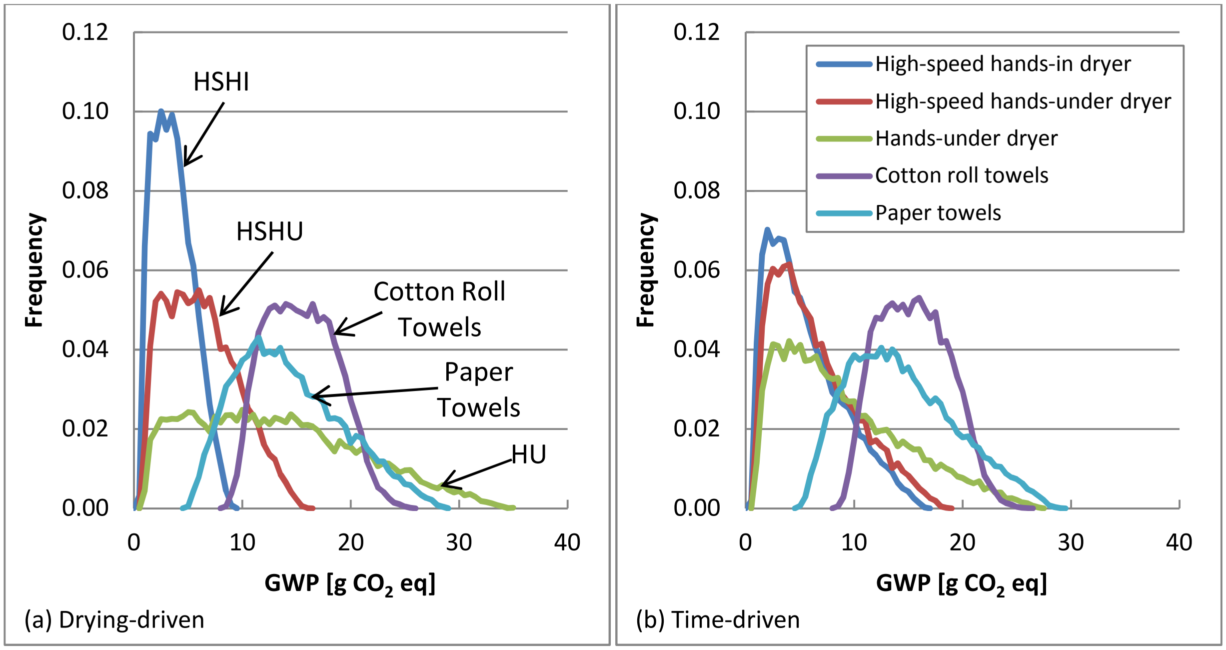
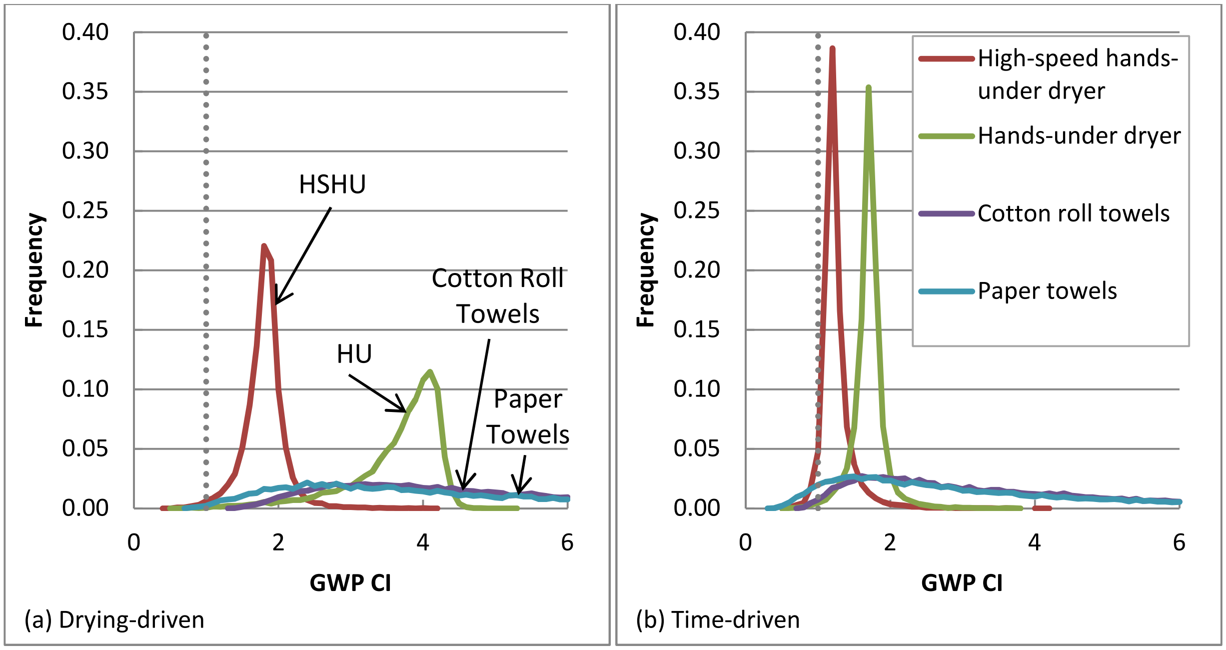


Fig. 5 GWP frequency distributions given (a) drying-driven and (b) time-driven usage patterns. Both plots are based on correlated use intensities and different printed wiring boards for the hand dryers (in accordance with meta-scenarios 1 and 4, respectively, from **Table 5**)



(a) Drying-driven

(b) Time-driven

Fig. 6 GWP comparison indicator (CI) frequency distributions (calculated relative to high-speed hands-in dryer) given (a) drying-driven and (b) time-driven usage patterns. The dashed line indicates a comparison indicator value of one as a reference. Both plots are based on correlated use intensities and different printed wiring boards for the hand dryers (in accordance with meta-scenarios 1 and 4, respectively, from **Table 5**)